SPATIAL AND TEMPORAL TRENDS OF SOIL MOISTURE IN THE GREAT LAKES REGION OF THE USA, 1900-2008

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ABSTRACT

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Soil moisture is a key integrative variable in natural and managed ecosystems, dependent on a location's climate, vegetative cover, soil type, topography, and other factors. A study of spatial and temporal variations in soil moisture in the Great Lakes region of the USA was undertaken to better understand the impacts of varying land cover and soil types as well as variations in climate. Soil moisture was simulated with the Soil Water and Assessment Tool (SWAT) model for 30 different combinations of land cover and soil types at 29 climate observation sites across the region for 1900-2008.

Significant increases in growing season soil moisture levels were found across much of the region during the study period associated with concurrent increases in precipitation. Some distinct changes in seasonality were also noted. The average date during the spring season on which soil moisture fell below field capacity is gradually occurring up to 18 days earlier in the year over the study period. Similarly, the dates at which the minimum soil moisture occurred each warm season and the date of recharge of soil moisture to field capacity late in the calendar year occurred up to 19 days earlier.

Collectively, the results suggest that soil moisture and plant available water across the region have increased with time with a corresponding decrease in the risk of water-related stress, which has important implications for plant-based agriculture and the management of natural resources.

To my wife Darlene, who has put up with the trials and tribulations of a lifetime student. It must be difficult listening to a husband who talks about things you have no knowledge of. I'm glad you had the patience and continued to listen.

Also, to my parents, Randall and Nancy Pollyea, who helped start my journey into higher education and have continued to support me today by spurring me forward, knowing I can be capable of anything I put my mind to. Who would have thought that a son who wanted to be an Astronomer his entire life, with his head amongst the stars, would fall back to Earth and into the clouds to study Climatology?

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INTRODUCTION

The Great Lakes region is an area dominated by large open bodies of water, large agricultural areas due to its fertile soils, a wide range of both man-made land covers such as field crops and urban environments, as well as more natural land covers such as heavily forested areas and open plains. This region was originally defined as the states of Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio, Pennsylvania, and Wisconsin by the United States Great Lakes Commission in 1955, though the Canadian provinces of Ontario and Quebec also sit on this commission as they are directly tied to the Great Lakes and associated waterways. The Great Lakes drainage basin is limited by the Mississippi Drainage basin to the west and the Ohio drainage basin to its south. This basin contains the entire state of Michigan and the areas of the Great Lakes states closest to the Lakes (Figure 28).

The climate of the region is influenced by long waves in the upper air flow and the warm season polar jet stream. These meteorological features are caused by temperature gradients in the west to east movement of the upper air (Rossby 1939). Variability in the Great Lake regions climate can be attributed to the position and strength of these long waves and the jet stream. These same features also affect which sources of air move into the region, be it warm moist air from the Gulf of Mexico, cool moist air from the Canadian Rocky Mountains, or cool dry air from Hudson Bay to the north or the Pacific Northwest. As this region is far away from the Gulf of Mexico, which is the source of much of the atmospheric moisture east of the Rocky Mountains, many of the states have some of the lowest amounts of annual precipitation in the United States, with Michigan 40th, Wisconsin 43rd, and Minnesota 47th out of 50. Short time-frame synoptic weather events such as cyclones (low pressure systems), anti-cyclones (high pressure systems) and short-waves (a feature that moves along a long-wave) also impact the climate of the region. Cyclones are very important to the annual precipitation totals in the study region as they can contribute over half of the annual precipitation totals. Mescoscale convective systems also contribute a significant portion of precipitation to the region, about 10% of the warm season totals. These events are large scale clusters of thunderstorms that can last for several hours or more. The largest portion of the annual precipitation totals occur during the mid to late warm season, thus these events have a large impact on the precipitation – evapotranspiration deficit. (Andresen and Winkler 2009)

The climate of the region is also directly influenced by the lakes. The lakes moderate temperatures in both the warm and cool seasons providing a more mild climate with less extremes downwind of the lakes when compared to areas further west such as the northern Great Plains and other continental climates. This moderation is due to the delay that the Lakes generally reach their maximum and minimum temperatures, generally 4 to 6 weeks after when the atmosphere reaches those values (Eichenlaub et al. 1990). The lakes also produce 'Lake Effect' snow during the cold season when cool air moves across the lakes and is warmed by the lake surface where it picks up more moisture. This moisture is then deposited when the land surface cools the air once again, mainly in the regions downwind of Lake Michigan and Lake Superior, with an increase in snowfall of between 25-30% (Changnon and Jones 1972). The lakes also produce changes in atmospheric drag in the air moving across them. When the air moves across the lake and then impacts on the downwind shoreline there is a reduction of the wind speed and could possibly produce vertical motion that goes on to produce lake effect clouds, most of them occurring in the autumn and cold season when the region is experiencing northwesterly winds. All of these modifications can occur together and produced enhanced results. (Andresen and Winkler 2009)

The land covers of the region can be described as mainly agricultural, with the land surface area for corn, soybeans, and pasture land accounting for nearly 20%, 15%, and 10% respectively, adding up to slightly over 40% of the land surface area when including all agricultural products. This is followed by forested areas, both evergreen and deciduous forests, that account for over a quarter of the surface, and then by open/pasture land with over 10% and finally urban areas with close to 10%. The soils are just as diverse. When looking at the soils that make up more than half of the land area in the Great Lakes we see that over 20% of this area is covered by Sand, Sandy Loam, and Silty Loam each. Loam soils make up slightly more than 12%, Clay Loams about 4%, and Silty Clay Loams make up only slightly more than 2%.

The Great Lakes region is an important component of our nations agricultural output. In 2007, the states of Indiana, Illinois, Iowa, Michigan, Minnesota, New York, Ohio, Pennsylvania, and Wisconsin combined produced over 63% of the US production of grain corn, 35% of the nation’s acreage of apple orchards, and over 87% of the nation’s acreage of tart cherry orchards to give some examples (USDA/NASS Census of Agriculture 2007). Since evapotranspiration is greater than the rate of precipitation during the warm season, all of these agricultural products depend on plant available water located in the soil. Georgakakos et al (1995) correctly stated that soil moisture found in the upper 2 meters of the soil column is the “primary hydrologic variable that controls and is controlled by land surface processes.”

Lack of this soil moisture can lead to lower crop yields or total crop loss in severe cases (Mishra and Cherkauer 2010). Drought, or the deficit of soil moisture caused by evapotranspiration outweighing precipitation on a predefined timescale, severity, and/or spatial scale, can be one of the most devastating natural disasters in economic terms. Sawyer (1964) said that almost half of the incoming solar radiation during the summer in mid-latitude regions goes directly into evapotranspiration. The estimated loss for the 1988 drought alone was $40 billion (American Meteorological Society, 1997). With the Great Lakes region being heavily dependent on agriculture, the idea of drought and lack of adequate soil moisture is one of the most important issues facing agricultural production and the economy of the Great Lakes.

Shown below is an idealized soil moisture curve that would be typical for many Northern Hemisphere locations including the Midwest of the United States (Figure 1). This simplified graph shows the reduction of moisture in the soil column during the spring due to increasing temperatures and increasing water use by a vegetative land cover (ET, i.e. evapotranspiration). It also shows the recharge of moisture in the soil column during the early fall to winter due to decreasing vegetative water use and cooling temperatures leading to lower ET. Finally, this image also shows a potential plant moisture stress that is caused by a lack of water that is easily accessible to a generic plant at the surface. The basic concepts of this image will be revisited later in the paper.

Previous studies of Drought and Pluvial

First we must define plant available soil moisture as it is defined differently than soil moisture. Soil moisture is the total amount of water in the soil column. Rodriguez-Iturbe and Porporato (2004) correctly state that soil moisture is “the center of the hydrologic cycle”. This is in contrast to plant available soil moisture which measures the moisture that a plant can draw out of the soil column, which means that plant available soil moisture is a lower total then the values given by soil moisture. What this also means that while there can be water in the soil column, a plant may not be able to utilize any of it and will become water stressed due to a decrease in transpiration.

During the 20^{th} Century there have been many definitions of drought for many different purposes and all using different techniques in an attempt to quantify the deficit of precipitation compared to evapotranspiration. Landsberg (1982) summarized it well when he said, “No universal definition of drought exists…one can say that drought is a term generally restricted to land areas where some form of agriculture, horticulture or silviculture is possible.” But still this doesn’t cover many of the ways the term drought has been used. Heim (2002) better summarizes drought categories into four types: meteorological, hydrological, agricultural, and socio-economic. What all of these drought indices try and bring together is the idea that water entering the soil column, from above as precipitation or from below as water returning from a shallow aquifer, has an impact on the quality of the land or the quality of land use. The most direct way of describing these impacts is through understanding or simulating plant available water.

Rodriguez-Iturbe (2000) summed up soil moisture well when he said that one could provide a “description of soil moisture at a point as a function of climate, soil, and vegetation.” The attempt to describe drought or the reduction of plant available soil moisture due to differences between precipitation and evapotranspiration over a large surface area and a large period of time is difficult as that none of these indices mentioned previously can perform an adequate job of comparing one site to another. Nor can an adequate job attempting to describe an abundance of moisture in the soil column.

Beven and Kirby (1979) were able to show that topography had a significant impact on the scale at which soil moisture varies spatially, both in surface roughness and the overall slope of the landscape. Topography was then grouped with other variables such as vegetation, soil texture and other soil characteristics. Everything else was considered atmospheric forcing, i.e. meteorology including precipitation or melt water, temperature, wind speed and relative humidity, evapotranspiration, and finally incoming solar radiation. These two groupings had different temporal and spatial scales.

Rodriguez-Iturbe and Porporato (2004) said that “The interaction between water balance and plants is responsible for some of the fundamental differences among various biomes and for the developments of their space-time patterns.” Differences in soil characteristics, even inside the same soil class, and even inside the same field, can be enough to impact soil moisture calculations. Differences in land cover, such as tree density, tree albedo, and differing slopes also can lead to differences in soil moisture and associated indices in the same stand of trees.

Plant available soil moisture, and soil moisture overall, have a direct impact on many climate variables including precipitation, temperature, and relative humidity, and vice versa. Rand (1982) determined that soil moisture was important in forecasting summer time temperatures and precipitation. A negative deviation from normal resulted in higher temperatures in the early summer months and decreased the amounts of precipitation. Rowntree and Bolton (1983) also concluded in their study of atmospheric responses to soil moisture in Europe that soil moisture can have a significant impact on precipitation, relative humidity and temperature in the area of the region in question. Delworth and Manabe (1988) came to similar conclusions when they found that soil moisture is important in determining the variability of summer time air temperatures. They also showed that changes in soil moisture can directly lead to air temperature variation by changing the proportion of energy transfer between latent and sensible fluxes. Findell and Eltahir (1997) found in their study of soil moisture feedback with precipitation that there was a significant linear correlation between soil saturation conditions and later precipitation during the summer months. Pan et al (1995) also came to a similar conclusion in a two year study. Georgakakos et al (1995) and Cayan and Georgakakos (1995) found that there was a non-linear and complex relationship between soil moisture and both temperature and precipitation, i.e. evapotranspiration.

Lettenmaier et al (1994) showed that when studying the Historical Climate Network observation sites from 1948 to 1988 that there was increasing temperatures west of Lake

Michigan and increasing precipitation west of Lake Erie. They also found that the increases in precipitation took place in the non-winter months. Karl and Knight (1998) came to the conclusion in their study stating, "Increases in total precipitation are strongly affected by increases in both frequency and intensity of heavy and extreme precipitation events." They also found that the frequency of precipitation has increased by over 6 days per century. Groisman et al (2004) found that the trend in precipitation showed an increase of between 7% and 15% nationwide as well as a 14% to 20% increase in Heavy (95^{th} percentile) and Very Heavy (99^{th} percentile) precipitation events. The increase in these events can increase the amount of surface run-off and change the water balance of a soil column. This same paper showed that an earlier spring thaw, of two to three weeks, allowed snow cover and spring to have an earlier onset. Giorgi (2000) and Groisman et al (2004) found that there were significant warming trends over North America and a positive trend in precipitation.

These trends in precipitation can have significant effects on soil moisture not just due to the increase in incoming water to the top of the column, but also reducing the amount of evapotranspiration that can occur due to lower incoming solar radiation. There is also a non-linear relationship between precipitation and surface runoff that is dependent on the saturation of the soil column (Georgakakos et al 1995). A large amount of rainfall can produce very little flooding or surface run off if the soil is well below field capacity, but even a moderate amount of rainfall can have the opposite outcome if the soil is near saturation.

Plant available soil moisture is vitally important to agriculture, Hollinger and Isard (1994) stated this fact. But accurate measurements of soil moisture are difficult at both the spatial and temporal scale to simulate due to microclimate, highly variable soils (all with different water holding characteristics), and highly variable land covers. These highly variable soils and land covers are the primary difficulty in any comparison of soil moisture and how it is changing over time.

Previous studies with soil moisture and soil moisture simulation.

Of particular interest to this study is the paper by DeLiberty and Legates (2003) in which they determined if soil moisture could be simulated with readily available data and to determine soil moisture climatology in Oklahoma using SWAT (Soil Water Assessment Tool). This is similar to this study, but with a more limited geographical range and different region than the Great Lakes (the state of Oklahoma) and a more limited time scale (1960 to 1991). They also used specific soil and land cover types at each of their climate observation sites. In order to geographically represent their findings, they used an inverse distance weighting method to interpolate their simulated data. The results of their study found that there was a significant impact on a year’s average soil moisture when there was a drier autumn that had a lower amount of recharge.

Along with Entin *et al* (2000), they examined the temporal scale at which soil moisture anomalies occur. DeLiberty and Legates found a scale of 1.8 months in Oklahoma and Entin *et al* found a scale of approximately 1.5 to 2.0 months in Iowa and 2.0 to 2.3 months for Illinois. Narasimhan et al (2005) used SWAT in their paper to provide a simulation for six drainage basins in Texas. They found that SWAT worked well for simulating stream flow and its simulated soil moisture was well correlated with NDVI, a satellite measured vegetation index used to determine plant health.

In a paper on soil moisture in root-zone soil moisture, Jayawickreme et al (2008) studied the interaction of land cover over different seasons in East Lansing, MI. They found that during the winter soil moisture moved downwards in the soil column. During the spring thaw soil conditions were stable or increasing in soil moisture content due to snow melt, and in the grassland land cover, were at or near field capacity. Using the VIC (Variable Infiltration Capacity) model to generate soil moisture, Sheffield and Wood (2008) found that the central United States had increasing soil moisture on the order of 0.05% to 0.2% volume per year, and that these were correlated significantly with increasing trends in precipitation.

Objective questions to be answered

In this study, using individual climate observation site data, there are multiple subjects explored. The study will explore how precipitation is changing over the time frame of 1900-2008 as well as spatially in the Great Lakes region. This study will then examine how plant available soil moisture is changing both temporally and spatially over the same study region using multiple generalized soils and differing land covers. Then the question of how the overall wetness of a year is changing over time along with if dry conditions over the Great Lakes area are getting longer and drier or shorter and wetter will be answered. Finally, the temporal scale of soil moisture anomalies will also be examined.

This knowledge is of great importance as knowing the overall trend of how soil moisture is changing could affect the dates in which agricultural crops are planted and possible water stress on those plants. Knowing water stress on plants can also affect the amount of irrigation that producers may need to use. This is a vital piece of information for the economics of agriculture due to increased or decreased water stress on the crop, the frequency and amount of irrigation needed, and the ongoing debate of water rights.

METHODS

In general, comprehensive observations of soil moisture are not available over extended periods of time in the Great Lakes region study area. For this study, a process-based simulation model, the Soil Water Assessment Tool (SWAT) was used to estimate soil moisture in the top 150 cm of the soil profile across a wide variety of representative climates, soils, and land cover types across the project domain. While the use of simulation models may provide good estimates of reality under a wide range of hypothetical conditions, such efforts are complicated by both the very large number of processes and phenomena involved in the system dynamics and = extremely large variability in time and space.(Rodriguez-Iturbe and Porporato, 2004)

Use of SWAT (Soil Water Assessment Tool)

The Soil Water Assessment Tool (SWAT) is a process-based simulation model originally developed by the USDA that is used to simulate soil moisture with soils and land covers over large watersheds and over long continuous periods of time. The original version of SWAT is a successor of the USDA's CREAMS model (Chemicals, Runoff, and Erosion from Agricultural Management Systems (Knisel et al. 1980) as well as other precursor models including GLEAMS, EPIC, and SWRRB (Arnold et al. 1998).

The primary physical strategy behind the SWAT model is the standard water balance state equation: $SW_t = SW_{t-1} + \sum_{t-1}^{t} (R_i - Q_i - ET_i - P_i - QR_i)$.

Where SW is plant available soil water, R is precipitation, Q is runoff, ET is evapotranspiration, P is percolation and QR is return flow. SWAT can simultaneously simulate of to eight large segments of a watershed of a sub-basin, referred to as HRUs, or

Hydrological Response Units. The properties of the land cover and soils are either predefined in the models data base or they can be user defined. Further details describing the SWAT model can be found in Arnold et al (1998).

SWAT has been used in a wide variety of applications since its development ranging from soil erosion to estimation of soil moisture to river basin hydrology to other water-related applications (Gassman et al 2007). Several previous studies have used SWAT to simulate soil moisture, with the model performing well under a number of applications. For example, Narasimhan and Sirnivasan (2005) used SWAT to simulate soil moisture in Texas in order to estimate the Soil Moisture Deficit Index (SMDI) and the Evapotranspiration Deficit Index (ETDI). They concluded that SWAT preformed well as determined by the correlation with NDVI (Normalized Difference Vegetation Index) for agriculture and pasture type land covers. DeLiberty and Legates (2003) used SWAT in a study of soil moisture variability and soil moisture climatology to estimate the temporal scale of soil moisture variation in Oklahoma for both historical and projected future time frames. They found that SWAT estimated soil moisture magnitude and variability accurately over a wide range of conditions. SWAT has been commonly used in Total Maximum Daily Load (TMDL) analyses, assessing the effectiveness of USDA soil conservation efforts, and to perform large scale assessments of base flow and snow melt for very large river basins (Gassman et al 2007). However, the model does require a significant amount of input parameterization and other information in order to operate properly. In addition, the developers of the model (Arnold et al 1998) stated that while SWAT uses easily available inputs for large areas, is computationally simple to run on large basins, and simulate for long periods of time, it also requires proper calibration. A summary of previous studies using SWAT can be found in Gassman et al (2007).

In this study, the SWAT model was set up to simulate soil moisture across the Great Lakes region for a number of climates, soils, and land cover types. Thirty HRUs were utilized for the simulations. The time period of 1900-2008 was chosen for the study time frame, which includes the great historic droughts of the 1930's across the region (Andresen et al., 2001) as well as recent major droughts in 1988 and 2005 (Mishra and Cherkauer, 2010) and a relatively wet period during the past 1-2 decades (Andresen, 2012). The start of the study at the beginning of the 20th century also allows examination of trends that began before the 1930's time frame back to the beginning of the period of large numbers of reliable instrumental records across the region (Andresen, 2012).

Climate Data

Climate variables needed by SWAT as input are daily maximum and minimum temperatures, precipitation, total solar radiation on a horizontal surface, average relative humidity and average wind speed. The primary data needed for simulation in SWAT, daily maximum and minimum temperatures and total precipitation, were obtained from the Daily Global Historical Climate Network (GHCN), a high quality, long term record of daily climate data across the USA (Menne et al 2011). For the study time frame, 29 climate observation sites were chosen for their geographical distribution and climate record completeness over the Great Lakes region and surrounding areas (Figure 17). The geographical range of the climate observation sites spans an area from 40.6 to 47.0 degrees north latitude and 75.9 to 94.1 degrees west longitude. At least one station site was chosen for each state in the Great Lakes region as well as bordering states if they were available for the time period. Both Clinton and Fayette, Iowa as well as Pine River, Minnesota (all to the west of the actual Great Lakes basin itself) were included in this study to better account for the east to west precipitation gradient that exists across the region. Besides the spatial distribution of the observation sites, the other major criterion utilized in the selection of study sites was the amount of missing data in the site records as determined by data analysis in a database program by the author. Other input climate variables, solar radiation, relative humidity, and wind speed, were generated synthetically. Solar radiation was simulated with the WGEN stochastic weather generator (Richardson and Wright 1984) following the method of Andresen et al (2001). Daily average wind speed and relative humidity, needed to estimate potential evapotranspiration (ET) in the model using the Penman-Monteith estimation method, were generated synthetically using the WXGEN climate generator given information from a statistical database for the USA (Sharply and Williams, 1990). Missing climate data estimates were obtained with data from representative neighboring observing based on distance to the original observation site and similarities in terrain.

Observed climate variables from climate stations that are a part of the Historical Climate Network were used rather than upscaled gridded data.

Two spatial scales of climate data were initially considered for use in this study: gridded and point level data (i.e. data from individual climate observation sites). Many studies of drought and soil moisture content have utilized data from individual locations (i.e. climate observing sites), and then spatially averaged over grid cells of varying scales.

In their study of 20th century drought in the US, Andreadis et. al (2005) used 2489 weather stations for daily precipitation and 1904 stations for daily temperature data that were then averaged over a 0.5 degree resolution grid. DeLiberty and Legates (2003), in their study on variability of soil moisture, used an inverse-weighted method for interpolating data from individual climate observation sites and concluded that it overcame several significant limitations of traditional weighted-average approaches, accounted for the sphericity of the Earth, and was one of the most reliable techniques for estimating daily precipitation. On the other hand, gridded data offer the potential advantage of spatially and temporally complete series records, even though the base data on which they are based may vary over time.

In a preliminary comparison study of point-based vs. gridded data to determine which data set would be more representative, Upscaled, gridded climate data was obtained from Midwestern Regional Climate Center (http://mcc.sws.uiuc.edu/) for the time period of 1900-2008. Data was provided with a scale of 2/3rds of a degree latitude and 1 degree of longitude (Figure 16 for map of the locations of the center of the grids). This data was then analyzed for any inconsistencies, errors and incongruities which then showed several things that are worth noting.

The interpolation of precipitation records from observation sites (data obtained from Historical Climate Network) inside the grid boxes (Kunkel et. al. 2005) caused the ratio of wet days with recorded precipitation to dry days that were much higher than expected (Table 3) for the time period of 1900-2009 and across a selection of 10 stations across the study region. Of the grid boxes checked the highest ratio seen was 2.08 times greater than observed at Rogers City, MI and the lowest ratio was 1.57 times greater at both Alpena and Ann Arbor, MI. In contrast, it was seen that the precipitation totals were fairly close to the measured amounts with values ranging from 0.94 (Grayling, MI) to 1.16 (Wilkes Barre, PA) times the normal observed amounts.

Based on the results of the preliminary study, the individual, point-based data were chosen for this study due to the relative increase in precipitation frequency and reduction in precipitation amounts associated with gridded data, which could lead to a number of changes in the simulation including reduced runoff for the gridded data and interception of precipitation by the plant canopy, changes in antecedent soil moisture and infiltration, and potential changes in the amount of Potential Evapotranspiration (PET). It was also observed that in some cases the gridded minimum daily temperature exceeded the maximum daily temperature (due to observation time differences in station series used to compute the spatial averages). This problem was found to be relatively more common early in the study period of record when there were lower numbers of climate observation sites available inside the grid box.

One of the most difficult challenges in simulating soil moisture is accounting for physical soil characteristics that may vary considerably over only short distances (Cambardella et al 1994). Over a large study area such as the Great Lakes region, SWAT's computationally heavy processes could be a liability (Arnold et. al. 1998). To account for the potentially large variations in soils across the study domain, SWAT was run at each individual site for 6 soils representing a textural range from a coarse-textured sand to a fine-textured clay loam, which are representative of the wide variety of soil types found in the Great Lakes basin. Each soil was defined in the simulation to be 1500 mm in depth and with homogeneous textural characteristics throughout the column. Even though a homogeneous soil column is unlikely to be observed, the model estimations are then more directly comparable between study sites. The physical characteristics of these soils can be found in Table 5, with a total range of 107 mm (sand) – 309 mm (silt clay loam) of plant extractable water for a 1500 mm profile. The soils used will often be referred to in the text and tables of this paper by abbreviations in order to be succinct. Sand, S; Sandy Loam, SL; Loam, L; Silt Loam, SiL; Silt Clay Loam, SiCL; Clay Loam, CL. For all simulations, a single small, relatively flat basin with less than 1 degree average slope was assumed at each study site.

SWAT also takes land surface vegetative cover type into account as an input variable. Five land cover types were chosen represent typical land covers found across the Great Lakes region. As noted previously, the Great Lakes region is home to a significant portion of the nation’s agriculture. To simulate soil moisture on agricultural landscapes, three land covers were selected: corn (for grain), grass-based pasture, and winter wheat. Winter wheat was specifically chosen as it is a fall-planted crop unlike the others which are planted in the spring season. The two other land covers used were mixed forest (which includes oak and pine) and urban (medium-density residential). These land covers were used to represent a range of common surface types in the region, but also to examine the hydrologic differences between differing surface types (e.g. runoff from forested surfaces tends to be relatively lower than runoff from paved urban areas. For all cover types except corn, the physical parameterization provided in the SWAT modeling software was used. For corn more modern values typical of current productions systems were used. The biomass to energy ratio was increased from 39 to 45 (kg/ha)/(MJ/m^2) (Loomis and Amthor 1999), the maximum leaf area was increased from 3.00 to 5.35, and maximum canopy height and maximum rooting depth were changed to 2.75m and 1.5m respectively in order for the model to simulate realistic biomass totals (Grant and Hesketh 1992 for canopy height and LAI, and Canadell et al 1996 for rooting depth). Applied amounts of nitrogen and phosphorus were each assumed to be unlimited in this study, and the model was automatically set to apply fertilizer anytime nutrient stress was detected. This procedure was applied to isolate the effects of climate, soil type, and land cover type.

Prior to the application of SWAT across the study domain, the model was calibrated and validated with a set of observed soil moisture data obtained from the Illinois Climate Network (Hollinger et. al 1994), which maintains 17 observation sites across the state of Illinois. Observation frequency at the network sites varies from monthly or bi-weekly observations to daily. Three soil moisture observation series were chosen from the dataset based on their observation frequencies, periods of record, and soil types: Bondville, Champaign, and Topeka. Soil series at these observation sites are Elburn silt loam, Drummer silty clay loam, and Uldolpho Fine Sandy Loam, respectively. Soil moisture and climate data was collected from each site for the period of record of 1989-2009. Climate data was then entered into the SWAT model along with soil parameters of the observation sites and a pasture land cover. The observed amount of soil moisture in the soil column was then compared to the same variable from the SWAT output on a daily basis for the period of record studied.

The initial results were not encouraging. The simulated plant available soil moisture agreed with field capacity and near saturation levels of plant available soil water, but SWAT estimates tended to over-estimate the soil moisture during observed drier periods by more than 15% of total plant available soil moisture when averaged over the entire year and ~20% absolute difference.

Internal variables, such as ESCO (soil evaporation compensation coefficient) in the model itself had to be adjusted in order to allow SWAT to draw water from deeper in the water column to meet evaporative demand. The result of these changes was a very close agreement between the simulated and observed values (Table 4 and Figures 18a, 18b, 18c) with differences of 5 mm of plant available soil moisture or less on average over the study period, less than 3% of total plant available soil moisture in the soil column and ~ 12% absolute difference, a great improvement over the initial model output. It was seen that these results were similar to both the yearly variation in plant available soil moisture and the magnitude of the change in soil moisture. This meant that SWAT was a logical choice to continue to use.

But SWAT was found to have limitations that make its use difficult in some circumstances. Rainfall that occurs over midnight is broken into the two days in which it occurs; this causes a lower amount of precipitation to be recorded for both days. This limitation also can be a part of the observed data set. Large sub-basins make simulating run-off difficult due to varying soil types and saturated conductivity as well as differing land covers and management styles of those land covers. Finally, soil composition and other data aren't often available at the spatial scales for large basins to be able to describe infiltration of water over a large basin (Arnold et al, 1998).

Modifications to the SWAT base code, as shown in Baumgart (2005), were needed due to the model not allowing crops to properly uptake Nitrogen and Phosphorous fertilizer when there was nutrient stress, as well as the previously mentioned problems. These elements were intentionally set as unlimited in the model in order to isolate the effects of climate and land cover on soil moisture without the influence of soil fertility. Allowing unlimited fertility allows the Corn and Wheat crop land covers to fully develop and achieve yields on par with observed amounts with results of between 5.0 to 8.5 t/ha for corn, and 3.7 – 6.9 t/ha for winter wheat (United States Department of Agriculture, 2009).

Another modification, from the same source, allowed accurate use of crop growth models inside of SWAT when air temperature was below the base temperature of the crop. This change allowed crops to grow if the temperature dropped below this minimum value after planting, rather than having a crop failure in that year. There were many cases seen where the model would suffer from this, more so in climatologically cool years. Another change was needed to help the model function properly when dealing with soil temperatures. Soil temperatures in the base model were under estimated when compared to observed readings. This also caused the soil to stay frozen longer which also led into the crop growth issues previously mentioned above. Finally, a code issue was also found in which SWAT would replace observed temperatures of $0^{o}C$ with a simulated temperature using the internal WXGEN weather generation model. This replacement was undesirable in that it could affect snow melt by increasing this value above or below the freezing point.

In order to examine spatial patterns of the model output across the study region, a type of spatial interpolation was necessary. In a previous study, DeLiberty and Legates (2003) used an inverse-weighted method, as shown in Shepard (1968), for interpolating data after concluding that it overcame several significant limitations of traditional weighted-average approaches, accounted for the sphericity of the Earth, and is one of the most reliable techniques for estimating daily precipitation. One very common objective analysis technique is the spline method. In a study by Hartkamp et al (1999), splining was described as "… a deterministic, locally stochastic interpolation technique that represents two dimensional curves on three dimensional surfaces (for other studies see: Eckstein 1989; Hutchinson and Gessler 1994). Splining may be thought of as the mathematical equivalent of fitting a long flexible ruler to a series of data points. Like its physical counterpart, the mathematical spline function is constrained at defined points."

The authors recommend splining because inverse distance weighting has no error surface and kriging, an interpolative technique to determine the value of a variable at an unknown point, requires a normal distribution. Price et al (2000) determined that the use of ANUSPLIN, a set of FORTRAN programs that uses splines in analysis of monthly mean precipitation, and monthly mean maximum and mean minimum temperatures across multiple climate stations, in Canada and the Great Lakes region, was appropriate. Price et al (2000) concluded that 'thin-plate smoothing splines such as ANUSPLIN enable better prediction in such regions because they calibrate a spatially varying dependence on elevation that uses all available data points.' For these reasons splining was chosen as a way to display spatial patterns.

In order to determine the temporal trends of the simulated output from SWAT, a type of regression analysis was needed to analyze the relationship of those variables over time. There are quite a few different techniques to achieve this goal, many of them described in detail in Lanzante (1996). One technique was used often in papers dealing with climate change, described in Sen 1968 (Hoaglin et al 1983, Gaffen and Ross 1999, Gahrs and Lanzante 2000, Gaffen and Wang 2001, etc), and called the 'median of pairwise slopes regression'. This is computed by finding the slope between all possible pairs of points and then taking the median of those values to determine the final slope. This technique was used in order to determine temporal trends in the modeled soil moisture data generated from SWAT.

Time Trend Analysis, Breakpoints.

A Standard Normal Homogeneity Test (SNHT) test was applied to the Precipitation data for each station to determine a break point where precipitation trends may have changed. This process was described in Khaliq and Ouarda (2007) as well as Alexandersson and Moberg (1997). Differences in the slope of the rate of change of precipitation could skew the results of any long term trend seen in the model output. For example, if yearly precipitation amounts were fairly static from 1900-1950 and then began to quickly rise. The rate of change for the entire time period would only show a mild overall change.

The results of this comparison showed that while there were breakpoints at the 95% and the 99% confidence level, they were not consistent across the study area, nor did every station show break points. 18 climate stations showed a break point at the 95% confidence interval and 12 showed the same at the 99% confidence interval. The average year in which these breaks occurred was 1965 and 1967 with a standard deviation of 28.2 and 23.8 years respectively (Table 6).

As it is seen, only 62% of the climate stations showed a breakpoint at even the 95% confidence interval. Even with looking at only these stations showed a large standard deviation. Any breakpoint would have to be applied across all climate stations and this would either not catch the breakpoint or place an artificial one where none existed. To move forward in determining any long term trends across spatial and temporal dimensions it was decided to not include a breakpoint.

Comparing results between soils or land covers

One of the first issues that comes up when attempting to view spatial data across multiple output dimensions, in this case land cover and soil types, is a way to best display it on a map for ease of understanding. In order to accomplish this goal, this study wished to see if there was a larger difference between comparisons of the model output of land covers and the differences in soil types.

Yearly results of the slope of variables generated by the model were combined under the same land covers (i.e. all six soils that were in each land cover) and under soils (i.e. all five land covers that were in each soil). A relative standard deviation test was performed on both groups. The results of this test showed that combining all soils in a specific land cover had a smaller relative standard deviation of the resultant slopes than combining all land covers under a specific soil (Table 7). The results are striking in that some variables show a whole order of magnitude difference in the same variable when comparing between groups of soils and groups of land covers.

Furthermore, differences between soils within each land cover type were explored. While all soils behave differently based on texture, it was seen that the rate at which a soil moisture variable changes over time is quite similar between soils. It is also seen that different textured soils behave in a very similar manner for both daily and yearly model time-steps (see the final column of Table 14 for examples).

The three moderately textured soils (SL, L, and SiL) behave closely together while the coarse and very fine textured soils (S, SiCL, and CL) tend to have a larger difference in their change over time then the overall average. It is seen that displaying the results of the average of the SL, L, SiL together would be a good way of geographically displaying the temporal trends simulated. Their yearly soil attributes closely resemble each other and generally fall in the center of the model results for these attributes.

For all of these yearly soil moisture variables we must keep in mind the soil water balance equation: $SW_t = SW_{t-1} + \sum_{t-1}^{t} (R_i - Q_i - ET_i - P_i - QR_i)$.

RESULTS AND DISCUSSION

In order to properly understand the changes in soil moisture across the Great Lakes region, one must first look at a baseline of climate variables and derived hydrologic variables to better gauge the relative scale of the changes. Annual temperature and precipitation totals for each of the study sites was averaged over a 1979 to 2008 time frame. Further, precipitation and its trends drive each aspect of the hydrologic variables of evapotranspiration, runoff and drainage.

Precipitation and Temperature

As was written earlier, Rodriguez-Iturbe and Porporato (2004) have stated that soil moisture is “the center of the hydrologic cycle”. The driving factor behind changes in soil moisture is primarily precipitation, and a lesser extent temperature through potential evapotranspiration (Delworth and Manabe 1988).

Precipitation is a more complex variable spatially across the Great Lakes region. The far eastern sections of the study region (New York, Pennsylvania, and eastern Ohio) have the greatest amounts of average annual precipitation. Further west precipitation totals are greater as you move from north to south. The differences can be attributed to both differences in synoptic weather patterns and relative nearness of the Gulf of Mexico as a source of moisture. (Andresen 2007)

The highest total average annual precipitation in this study is found at Warren, PA (1195 mm) and the lowest is found at Pine River, MN (724 mm), with a mean of all stations of 900 mm. (Figure 2)

Temperature is one of the primary driving variables behind the calculation of evapotranspiration, and one expects to see a north-south gradient. Temperature across the Great Lakes region in the 1979 to 2008 time period is fairly well behaved spatially. As is expected, there is a strong warming trend to average annual temperatures as you move further south, and a suggestion of a slight east to west warming trend that can be attributed to moving deeper into the continent (See Figure 3).

The warmest average annual (1979-2008) temperature in the study area is Delphi, IN with 11.2C, and the coolest average annual temperature can be found at Iron Wood, MI with 4.3C, and a mean of all stations of 7.9C.

Annual Spatial-Temporal Trends in Simulated Soil Statistics

Land cover can have a significant impact on soil moisture. Evapotranspiration rate, leaf interception, and infiltration rate can all be directly affected by the type of surface cover (Rodriguez-Iturbe et al, 1999). Averaging the soil moisture variables across soil textures for a given land cover shows the greatest amount of evapotranspiration occurring on the pasture land cover (593.3 mm) and the lowest on the winter wheat land cover (476.3 mm). Pastures long growing season and its peak growth in the warmest period of the year allows for this high ET and the lower temperatures surrounding the winter wheat help keep the ET value low for that land cover. The highest value for drainage is seen in the winter wheat land cover (354.9 mm) and lowest with the urban land cover (80.6 mm). The low water use of winter wheat in the warm and wet season helps increase the drainage value, and the overall impermeability of the urban land cover makes it difficult for surplus water to drain into the shallow aquifer. This same impermeability of the urban land cover makes it have the highest average value of surface runoff (313.1 mm) compared to the almost negligible amount of runoff seen for the forest (mixed northern hardwood in this case) land cover (3.2 mm) where the relatively high water use of the land cover keeps the upper soil layers dry and able to absorb precipitation and the trees themselves acting to block water from easily running off. (Table 1) The duration and timing of a crops growing season can change when the greatest water use can be expected. Winter Wheat, for example, can be expected to draw water from the soil column much earlier (and later) in the year than a typical Corn land cover. Another example is the interception of a land cover in determining the amount of water entering into the soil column during a precipitation event. An Urban land cover may behave in a similar manner to a Forested land cover for light precipitation events as the interception of leaves in the forest may be similar to the runoff generated by the impermeable surfaces of the urban terrain, but behave much differently under extreme precipitation events.

As can be seen in Figure 4 (Foth, 1990), soil type and texture can have a large influence on soil moisture in a given annual cycle. Soils that have a silt loam texture generally have the largest water holding capability of all soil textures, with the more extreme texture classes of sand and clay holding far less. The differences between sand and clay, however, are that sandy soils tend to hold water at higher water potentials than more moderately textured soils, and clay textured soils at lower water potentials. Given higher overall hydraulic conductivities, this also allows sandy soils to replenish water drawn out of the soil column by roots relatively quickly; while water removed from the soil column by roots on clay textured soil is more slowly replenished. Averaging the soil moisture variables across land cover types for a given soil texture shows that ET is highly dependent on the water holding capacity of the soil itself. The highest values can be seen with the Silty Clay Loam textured soil (570.1 mm) and the lowest on the Sandy textured soil (471.6 mm). Drainage is inversely related to plant available water holding capacity as larger pore sizes allow less water holding and more drainage with the highest values on sandy soil (343.9 mm) and the lowest values on silty clay loam textured soil (222.5 mm). Finally, when averaged across land covers, runoff is affected by the pore space of the soil as well with the highest amount found on clay loam textured soils (113.6 mm) and the smallest on Sandy Loam soils (82.8 mm) (Table 2).

When analyzing the results of the SWAT model, the average of Sandy Loam, Loam, and Silty Loam soils are used as they are representative of all six soils. This holds true throughout the discussion, unless otherwise noted.

Evapotranspiration

Mean annual total evapotranspiration averaged across soils and seen in all land cover types is similar in pattern to average annual temperatures with a general increase from north to south and a slight east to west increase as well. This trend is likely associated with the trend in mean annual temperatures as well as northeast to southwest increases in mean growing season solar radiation. Near the lakes, moderation of spring time temperatures keeps local conditions cooler than locations of the same latitude that are far from the lakes, allowing less ET to accumulate. And while the opposite is true in the fall, when temperatures near the lakes are slightly higher compared to other sites, most plant water use has trailed off as the plants goes into senescence. On a loamy texture soil with a grassland cover, the highest average annual ET value for the 1979 to 2008 period was at Delphi, IN (684 mm), the lowest was at Sault Ste Marie, MI (498 mm), and a mean across all stations of 602 mm. (Figure 5)

Runoff

Runoff shows in interesting spatial pattern when looked at across the 1979 to 2008 time period. Many different factors impact this simulated variable including amount of average annual precipitation (where higher values of precipitation occur, higher amounts of runoff are expected), and severity of precipitation events (heavy precipitation events would result in more runoff occurring then if the same amount of rainfall fell over a number of days). When comparing a grassland land cover on a loamy textured soil the eastern portion of the study area shows high run off (Watertown, NY having an average of 25.9 mm per year), and as you move west the amount of runoff decreases until a minimum value is reached at Wauseon, OH (5.7 mm). A significant ‘ridge’ of high runoff values can be found stretching from north-central Illinois (Aurora, IL with 20.3 mm) north to the western Upper Peninsula of Michigan (Ironwood, MI with 23.0 mm) (see Figure 6). Much of the pattern of runoff can be explained through the amount of precipitation that occurs in the fall season (September, October, and November and a correlation coefficient of 0.55 when comparing fall precipitation and runoff) when there is less evapotranspiration occurring, and the soil may be recharged.

Drainage

The average annual drainage, or the amount of soil water that flows downward and out from the bottom of the soil column in a given year, is very similar spatially to the pattern of average annual precipitation. In fact, when doing a simple correlation between average annual precipitation and drainage across all stations, there is a 0.92 correlation. When comparing a grassland land cover on a loamy textured soil, the highest values are found in the eastern portion of the study area with a maximum average annual value of 553.8 mm at Warren, PA. There is a strong east to west downward pattern with a minimum value of 163.8 mm at Pine River, MN. The mean value for the region is 286 mm. (Figure 7)

Time Averaged Inter-Annual Variables across time, 1979-2008.

A typical annual pattern for the seasonal drawdown and recharge of soil moisture at South Haven, MI Data were plotted in a 'box and whiskers' graph format for model-simulated values of daily soil moisture in the top 150cm of the soil profile during the year (Figure 8 above). The solid blue line is a 9-day moving average of the median value of soil moisture for a given day. The darker interior areas are the 25th to 75th percentiles of all the daily values, and the lighter areas extend out to the 10th and 90th percentiles. The beginning of soil moisture drawdown each year begins around day 50 (late February) with the total moisture reaching a seasonal minimum about day 190 (mid July). Replenishment/recharge begins at that point and continues until field capacity is reached once again near day 300 (late October).

One additional variable that will be discussed is 'Field Capacity Days'. This is the total amount of water in the soil column over a year expressed as the sum of the total amount of soil moisture for each day (mm * days). It is effectively the area of the soil moisture graph below the soil moisture curve, and describes how 'wet' any given year is.

Annual variables such as evapotranspiration, runoff, and drainage help explain water usage on a large temporal scale. But the inter-annual variables such as when the plant available soil moisture falls below field capacity in the spring, when the minimum amount of soil moisture occurs, when the date is that the soil is recharged to field capacity, and the number of field capacity days (discussed above) each year are extremely important when attempting to describe smaller temporal scale changes.

Day of Discharge

The day at which soil moisture in the top 150cm of the soil profile begins to drop below field capacity in the spring is referred to in this study as the 'Day of Discharge'. The variable has a strong association with spring temperatures as the warmer the spring, the faster snow will melt and the earlier ET can begin to accumulate. Thus there is a strong south to north trend with the latest Day of Discharges occurring in the northern sections of the study area. Averaged across all soil textures, the earliest Day of Discharge can be found at Norwalk, OH (Day 37.4, or February 6^{th}), and the latest can be found in Cheboygan, MI (Day 67.9, or March 9^{th}). The mean Day of Discharge is Day 53.6, or February 23^{rd}. (Figure 9)

Day of Minimum Soil Moisture

The timing of the minimum soil moisture value occurs each year is dependent on many variables: annual ET, seasonal temperatures, and seasonal precipitation to name just a few. The strongest correlation is between this variable and average summer temperatures across all study sites, land covers and soil types. There is a north-east to south-west decreasing (earlier) trend apparent in the 1979-2008 averages when looking at this variable geographically. The earliest value in the study area, when looking at a pasture land cover and averaging across soils is at Delphi, IN (Day 210.8, or July 30th) and the latest value is at Pine River, MI (Day 241.1, or August 29th) with a mean of Day 224.9 (August 13th).

Figure 10a and b shows two different land cover types, corn and wheat. As can be seen in the images the different land cover types affect the date of minimum soil moisture differently. As corn is a late season grower, it uses the largest quantities of water later in the summer whereas wheat uses it much earlier in the year. Corn has an average value of Day 195.1 (July 14th), a maximum of 223.4 (Aug 11th) and minimum of 176.7 (June 26th), while wheat has an average day of 166.9 (June 16th) a maximum of 198.3 (July 18th) and a minimum of 150.5 (May 31st). This is nearly a month difference for the average, maximum, and minimum dates between the two crops.

Minimum Amount of Soil Moisture

The minimum amount of soil moisture each year, like the day of occurrence, is dependent on many variables including ET, seasonal temperatures, seasonal precipitation, etc. There is a general north to south decrease in this variable, which makes sense as shorter growing seasons in the north translate into less seasonal ET accumulation and plant water use. The highest values of average annual minimum soil moisture were found in northern sites, with 80.7mm at Ironwood, MI and 80.5 mm at Two Harbors, MN. The lowest value was at Owosso, MI of 28.5 mm, and a geographical mean value of 43.1 mm. (Figure 11)

Day of Recharge

The day of recharge is the day at which the soil column returns to field capacity, and is dependent on seasonal precipitation, length of growing season, how dry the summer was, etc. There is much less of a spatial trend apparent in the 1979-2008 average of this variable. The earliest in the year that this occurs is found at Warren, PA on day 299.6 (October 27th), and the latest that it occurs is found at Cheboygan, MI on day 354.7 (December 20th) with a geographical mean of day 331.2 (November 27th). (Figure 12)

Soil Moisture Days

As was described previously, Soil Moisture Days is a way of looking at how wet a soil is over a given year. As it is the summation of daily soil moisture values, it is impacted by each variable that also impacts soil moisture. When examining the 1979-2008 averages spatially, there is a pattern that can be described. The lowest values (driest overall soils) can be found in the central part of the study region, Michigan, Indiana, Illinois, and eastern Wisconsin. The lowest value in the region can be found at Oconto, WI with 273.3 SMD. The highest values can be seen in the eastern and western areas of the study region with the highest value found at Ironwood, MI with 319.9 SMD. The spatial average of the study region is 290.4 SMD. (Figure 13)

Differences between Land Cover and Soil Types

Varying soil type can have a large influence on soil moisture in a given annual cycle, and thus, over long periods of time. Soils that have a silt loam texture generally have the largest water holding capability of all soil textures, with the more extreme texture classes of sand and clay holding far less. The differences between sand and clay, however, are that sandy soils tend to hold water at higher water potentials than more moderately textured soils, and clay textured soils at lower water potentials. This also allows sandy soils to replace water drawn out of the soil column by roots to be rapidly replaced, and water removed from the soil column by roots on a clay textured soil would only slowly be replaced (Foth, 1990).

Temporal Changes in Temperature and Precipitation

Spatial-Temporal Trends in Temperature

Across the 1900-2008 study period, temporal trends in average annual temperature across the region are spatially heterogeneous (Figure 14) ranging from -0.007 C/year to +0.017 C/year with an mean of 0.002 C/year. Overall, a larger number of observation sites showed an increase in temperature (14) compared to stations showing a decrease in temperature (12). Three stations showed no trend at all, and none of these were significant. This is not completely surprising, and agrees with previous research that has identified a number of shorter term trends within the 109-year study period, including a period of steady temperatures from the beginning of the 20th century to the 1930's, a slow drop in temperatures from the 1930's to the early 1980's, and finally a rapid warming from the 1980's onwards (Andresen 2007).

Spatial-Temporal Trends in Precipitation

Precipitation is the dominant influence on water for the soil moisture variables in the SWAT model. Overall, with only a few exceptions, annual precipitation was found to increase across the Great Lakes region during the period studied. (Table 26, Figure 19). The average rate of change for the entire study area was 0.733 mm/year. The majority, 24 of the 29 climate stations, had a positive slope with an average rate of change of 0.938 mm/year. 5 of the 29 stations had a negative slope with an average rate of change of -0.253 mm/year. 3 of the 5 that had negative precipitation slopes were found in Wisconsin. This shows that the vast majority of the study area became significantly wetter through the period of study. For example, the slope of 1.682 mm/year at Ann Arbor, MI, suggests an increase of 181.7 mm in annual precipitation over the study period.

The pattern of precipitation change over the study period when compared to the average annual precipitation amounts for the 1981-2010 is worth noting. The area with the greatest average annual precipitation in the study area is north-western Pennsylvania was associated with near level or slightly decreasing annual precipitation values trends. In contrast, show moderate to strong increases in annual precipitation were found in the driest regions in the study area, (the central Upper Peninsula, eastern sections of the Lower Peninsula of Michigan, east-central Minnesota, and north-western Wisconsin).

Evapotranspiration

Evapotranspiration (ET) is a combination of soil evaporation and transpiration from plants on a land surface, and as such, is dependent on both precipitation and temperature. As precipitation increases there is more moisture entering into the soil column for transpiration by plants. Increasing temperature increases the rate of evaporation from the surface of the soil.

The rate of ET is very different dependent on land cover type. In general, the most positive rates of change for ET were found on Urban land covers across all soil types, with a minimum value of -0.130 mm/year, a maximum of 0.811 mm/year and a mean of 0.248 mm/year, and the most negative rates of change were found on a forested land cover when looking across all soils, with a minimum value of -0.451 mm/year, a maximum of 0.579 mm/year and a mean of 0.064 mm/year (Table 18 and Figures 20 to 24).

Drainage

Drainage is defined as water which passes downward from the rooting zone It depends on both rainfall and antecedent soil moisture content, and as such is a stochastic, state-dependent component whose magnitude and temporal occurrence are controlled by the entire soil moisture dynamics (Rodriguez-Iturbe and Porporato, 2004) and is a good representation of how saturated the soils are through the annual cycle.

Temporal changes of drainage are similar to both the precipitation trends and the ET trends (Table 19 and Figures 25 to 29). Drainage increased across much of the study area, similar to precipitation. Decreases were observed in Central Wisconsin and eastern Iowa. The largest positive and negative trends across all soils were observed over the forest land cover (maximum of 1.82 mm/year, minimum of -0.41 mm/year, and an average of 0.69 mm/year).

Water Return

REVAP, as it is labeled in the SWAT model, is water which returns upward to the soil column from the shallow aquifer. This variable is a complex combination of the amount of precipitation occurring, when it occurs, and the depth of the rooting zone of the land cover. Rooting depth is an issue here as 2 of the land covers, corn and forest, have a rooting zone equal to or deeper than the simulated soil column.

Interestingly enough, each of the before mentioned land covers still closely resemble the other three land covers in spatial pattern of the rate of change and the scale of the rate of change. A mix of increasing and decreasing trends of water return was found across the region. Decreasing areas are the Upper Peninsula of Michigan and northern Wisconsin. Areas of increase are, depending on the land cover, the western and southern areas of the study region (Table 20 and Figures 30 to 34).

Across all soils the highest positive rates of change in water return are unsurprisingly seen in a forested land cover (maximum of 0.033 mm/year, minimum of -0.010 mm/year, and an average of 0.006 mm/year), as the trees draw water from the deepest portion of the soil column allowing moisture. The highest negative rates of change were found on a pasture surface (maximum of 0.03 mm/year, minimum of -0.018 mm/year, and an average of 0.005 mm/year).

Runoff

Runoff is the amount of water that leaves or enters the system by moving laterally across the surface of the land cover rather than infiltrating into the soil column. This is due to the impermeability of the surface, high antecedent soil moisture which prevents infiltration, or a combination of both. In general, yearly runoff trends closely resembled the yearly precipitation trends across the region. Almost no change in annual runoff was observed across the region over the period, while the urban land cover had the expected highest rate of change of annual runoff due to impermeable surfaces that followed the rate of change for precipitation.

Spatially, runoff increased across the entire study area with the highest amounts in northern Illinois and along the Lake Erie coast. Decreases were observed in central Wisconsin and eastern Iowa. (Table 21 and Figures 35 to 38). Both the maximum positive and negative trends in runoff were associated with the urban land cover across all soils (maximum of 1.045 mm/year, minimum of -0.325 mm/year, and an average of 0.351 mm/year).

Temporal Changes in Hydrologic Variables and Derived Variables.

Inter-annual Daily Trends – Summary

The change of soil moisture levels within a given year is complex. In order to detect any long term changes then each year a derived statistic such as the day at which discharge occurs must be examined and compared to previous years. Slowly a pattern begins to emerge that can describe the behavior of these statistics.

In modeling soil moisture, it is important to know how much soil moisture variation is caused by small temporal scale events and long temporal scale events in order to understand how accurate a model will be in reproducing expected soil moisture results and what scale the spatial and temporal resolution should be for the simulation (Entin et al 2000). Following the research of Entin et al (2000) and Deliberty and Legates (2003), the temporal scale was calculated using the procedures set forth in their studies. In the Entin et al study, they found a temporal scale of between 1.3 to 2.1 months for the upper 1m of soil in Iowa and Illinois. The Deliberty and Legates study found, for Oklahoma, a

1.8 month temporal scale. In this study the results correspond with the previous studies results fairly closely. Between all of the soils the average temporal scale across all the sites ranged from 1.35 months (41 days) for a corn land cover to 1.93 months (61 days) for an urban land cover, with an average temporal scale across land covers and soils of 1.65 months (50 days). See Table 24 for more detailed results.

Additional seasonal soil moisture variables examined in the study for changes over time were: the day of year when the soil first begins to fall from field capacity, the rate of discharge of soil moisture from the beginning of use until the minimum value of the year, the day of year when the minimum soil water value is reached, the rate of recharge of soil moisture from the day of that minimum value back to field capacity, and the day of year when the soils field capacity is reached. Finally there is the summed number of days at or above field capacity. Examples from selected stations can be found on Tables 22 and 23 in the Appendix for all of these variables.

Day of Discharge and Discharge Rate Trends and Patterns

This study examined the day of year when the soil water began to decrease from field capacity. If the soil moisture fell below field capacity and then returned to field capacity before falling again, the day of year was then taken as the latter value. After these dates were obtained, a pair-wise step regression was performed as described above to calculate trends and rates of change for the study period.

The spatial patterns for the rate of change for the date at which this start of discharge occurs were found to be dependent on the land cover used. Positive rates of change, meaning that the date at which discharge begins is increasingly later in the year, were observed in southern Wisconsin across land cover types. This same pattern can be seen in the Saginaw Bay area of Michigan except for forest and urban land covers. Negative trends were observed across the rest of the study, with discharge beginning earlier in the year. The most negative trends are in south-east Michigan and the Pine River Dam area of Minnesota (Figures 39 to 43).

The observed changes are noteworthy. For example, at Ann Arbor, MI, the rate of change of -0.0991 days / year for a corn land cover translates into a 10.7 day shift earlier in the year during the study period. With the same land cover in Viroqua, WI the shift was 1.1 days later in the year. Across soil types, the largest positive trend is 0.104 days/year found on a pasture land cover at Viroqua, WI, and the largest negative trend is also on the pasture land cover with a trend of -0.269 days/year found at Pine River, MN.

The rate of discharge is obtained as the total amount of soil moisture lost each year between the day of year where soil moisture first begins to fall in the soil column and through the day of year where the minimum amount of soil moisture is reached. While each soil texture class has differing field capacities and minimum plant available water values, the magnitude of the rate of change for this calculated variable is very similar. The trends for this variable are quite small, on the order of μm/(day*year).

Spatially the patterns are dissimilar, as can be expected, over the differing land covers. The greatest trend change can be seen in a wheat land cover as it begins its water use earlier in the warm season, thus drawing the soil moisture down earlier. The smallest trend changes over the study period can be found with the urban land cover. The rate of change is the highest in southern Wisconsin, the central Upper Peninsula and Saginaw

Bay area of Michigan (Figures 44 to 48). Across all soils, the largest positive change in the rate of discharge is 2.77 μm/(day*year) found at Pine River, MN on forested land cover, and the largest negative trend is -1.55 μm/(day*year) found at Fond du Lac, WI on the Wheat land cover.

When temperatures begin to increase seasonally in the late winter / early spring, snowmelt and relatively low ET ensure that the soil column is saturated. Overall, the start of soil moisture discharge across most of the region has become earlier by 1-2 weeks or more during the study period. As to the physical causality behind these changes, one major suspect is temperature trends across the observation locations (Table 25). As can be seen in Figures 52-56, there is a strong correlation between higher rates of change for average yearly temperature and the date of the beginning of discharge. Higher temperatures cause ET to begin earlier in the year; it can also cause snow melt to occur earlier, allowing the spring recharge to end earlier. The same pattern can be seen when looking at the rate of discharge against both the maximum and minimum temperature rates of change, which are strongly correlated. None of the other variables were correlated with changes in temperatures at any level of significance except for the Day of Year where soil moisture reaches field capacity against maximum temperatures.

Comparison of these variables against the rate of change of yearly precipitation (Table 26) results in correlations that is much higher than temperature as a whole. This stands to reason as precipitation is the major driving force behind changes in soil moisture. But it is interesting to see that there is a higher correlation with minimum temperature when compared to the rate of change of the rate of discharge, and the rate of change of the day of minimum soil moisture when compared to any of the temperature slopes. These are both variables that occur during the first half of the year. This could be caused by lower plant ET in the early part of the year making temperature the driving force rather than the gain or loss of moisture from precipitation.

Day of Minimum Soil Moisture Trends and Patterns

The timing of the minimum amount of soil moisture each season is an important to know for water management and irrigation scheduling. It is also the date at which the soil begins to recharge due to decreased ET or increasing precipitation.

Changes in the timing of the date of minimum soil moisture were found to differ widely across the various land covers, sometimes significantly. This is due to the either differences in the plants growing season and the changes in precipitation during those times (i.e. early in the spring for winter wheat, or later in the summer for corn, or the long growing season of the pasture and forest land covers). Trends towards earlier dates were observed across the land covers (towards over the Upper Peninsula of Michigan, and sections of northern Wisconsin and Minnesota (Figures 49 to 53). There were also differences between land covers such as a trend towards later dates on a pasture land cover in NE Michigan but negative trends on all other land covers and the Illinois stations showing near zero trends except for a winter wheat land cover. Across all soils, the largest positive rate of change is 0.11 days/year found on the urban land cover at Farmington, MN, and the largest negative rate of change is -0.17 days/year found at Big Rapids, MI on the pasture land cover. The differences in this variable appear to be associated with the timing of peak water usage during the growing season. Corn tends to use water earlier in the year due to rapid growth and canopy development when ET is increasing from increasing temperatures and still high values of plant available water. This is why the large portion of the study area has negative trends. The positive trends (getting later in the year) are associated with the same areas that are having a reduction of ET through steady temperatures, increased cloudiness and precipitation, etc.

For the forest land cover the date has generally come earlier in the year except for the stations near the Lake Erie and the northern Lake Michigan area. The earlier dates are especially associated with areas that are also experiencing some of the largest increases in ET. The more south-western areas that show this can also be explained by a general decreasing trend in precipitation during the autumn season or a lower rate of change then the surrounding areas (seasonal precipitation rates of change can be seen in Figures 69 to 72).

As pasture has a long growing season, many different variables impact the timing of its day of minimum soil moisture. The strongest trend towards an earlier day of year can be found in the western Lower Peninsula of Michigan, and the strongest trend towards a later day of year can be found in the eastern Lower Peninsula. A linear regression (with the rate of change of minimum soil moisture on a pasture land cover as the dependent variable) was performed with many rates of change of variables discussed in this paper in an attempt to describe the spatial behavior of this land cover and rate of change such as rate of change of ET, rate of change of runoff, rate of change in seasonal precipitation, etc. A model was developed that didn't explain a significant portion of the variability (r^2 of 0.56), but explained a high amount of that variability (p-value of 4e-4) using only yearly precipitation, ET, percolation and water being drawn back into the soil column. Each of these rates of change had at least a 95% confidence rating with ET and percolation above a 99% confidence rating with no co-linearity found between these variables. This suggests that as the rates of change of precipitation and water re-entering the soil column increase, and ET and percolation decrease that the date of minimum soil moisture gets later in the year.

Looking at the spatial distribution of this variable on an urban land cover there were also patterns that couldn’t easily be understood. This spatial distribution required another linear regression (with date of minimum soil moisture with an urban land cover as the dependent variable) to fully understand. A model was developed that didn’t explain a significant portion of the variability (r^2 of 0.34), but explained a high amount of that variability (p-value of 4.4e-3) using only the inverse rate of change for ET (99.8% confidence), and the rate of change for percolation (96.7% confidence) with no co-linearity found between these variables. This means that as average yearly ET decreases and percolation increases, the day of the year where the minimum soil moisture trends later in the year. This stands to reason as a higher ET would mean less water in the system throughout the year and more percolation means there is more often a greater amount of water then the soil column can hold.

The wheat land cover for this variable has very little spatial continuity across the study region. This complex variable surface also required a linear regression model to attempt to better explain the behavior. The linear regression showed that the rate of change of summer time precipitation had the greatest effect on the rate of change of the date of minimum soil water (96.4% confidence), but still explained very little of the actual variability (r^2 of 0.15). As summer precipitation increases, the date of minimum soil water gets later in the year. This makes sense when you consider that wheat has a growing season outside of the summer season.

Minimum Amount of Soil Moisture Trends and Patterns

As soil moisture decreases during the growing season, it can stress the plant life above it. But if the level of soil moisture at its minimum was getting higher or lower, the impact could be significant. The rate of change for the minimum amount of soil moisture was highly dependent on both soil type and land cover. Within a land cover category, the rate of change is consistently in the same direction, but the scale can be quite different. Because of the diversity of the results, we will confine our discussion to corn, forest, and wheat, which are representative of the range of the results (Figures 54 to 56 respectively). In general, there was a widespread increase in the minimum yearly value of soil moisture across the study area. The general exceptions are the Wisconsin observation sites and Upper Peninsula of Michigan, the southern observation sites, and in New York.

These are fairly striking results. For Ann Arbor, MI, the rate of change for corn on a loamy soil is 0.1301 mm/year and a beginning soil moisture value of 68.1 mm. This starting value increases to 82.2 mm at the end of the study period, of, an increase in the minimum plant available soil moisture of over 20%.

It is important to note that each of the combinations of land cover and soil types had a different outcome for the rate of change of the yearly minimum soil moisture. For corn there is a very distinct geographical distribution and steep slopes. As discussed earlier, using the rates of change of minimum soil moisture amount as the dependent variable in a linear regression against multiple independent variables was used to better explain the geographical distribution. We can see that this variable has a direct relationship with ET rates of change (>99.9% confidence rating) and annual precipitation. It does stand to reason that higher precipitation contributes to an overall higher ET. Combined with increasing temperatures this geographical distribution makes sense. The combination of temperature and precipitation trends is arguably the most important aspect of changes in minimum soil moisture trends in the study region. As precipitation increases, so does the amount of soil moisture. While the increasing temperatures help lengthen the growing season and increase ET, the lowering amount of water stress put on plants due to the increase in soil moisture is important to see.

The statistics for trends on forest were different. A longer growing season and a deeper root system made the water being drawn back into the soil column from the shallow aquifer more important to the rate of change (99.1% confidence). Combined with precipitation, to a lesser extent due to the higher interception by the leaf canopy, the rate of change for this land cover and soil is much more modest than corn on loam.

The third land cover looked at in this paper was wheat. Wheat is a more complex land cover in that the ET decreases significantly during the summer following maturity of the crop. The largest contributor to the spatial distribution of the rate of change was the water reentering the soil from the shallow aquifer (>99.9% confidence rating). To a lesser extent both the spring season and summer season precipitation contributes to the distribution with the summer precipitation inversely related. This inverse relationship is explained by understanding that higher amounts of rainfall in the summer contribute to a larger ET. Keeping ET low allows the shallow aquifer to better recharge the lower portions of the soil column, and having a great chance to increase the minimum soil water value.

Averaged across all soils the maximum positive rate of change for this variable is 0.207 mm/year found on the forest land cover at Fayette, IA, the maximum negative trend is -0.176 mm/year found on the corn land cover at Viroqua, WI. The average overall trend across all land covers and soils is 0.046 mm/year.

Day of Recharge and Rate of Recharge Trends and Patterns

As the growing season comes to a close the level of soil moisture begins to increase. The amount and frequency of precipitation also adds to the increase. The rate of change of seasonal recharge, the increase of the soil moisture from its minimum value back to field capacity was examined was found to vary across the region. Negative rates of change (recharge happening less quickly with time) were observed in the southern areas of the study region with the wheat land cover. The highest positive rates of change (recharge happening more quickly) are found in northern Wisconsin, the Upper Peninsula of Michigan, and northern Minnesota for the corn and winter wheat land covers. One commonality across all land covers was a positive rate of change in many areas of Michigan (Figures 57 to 61).

The day of recharge describes when the soil has finally recharged to its field capacity. For this region, this typically occurs during the early fall to the early winter. A relatively later recharge date during the next year’s spring was uncommon. Out of all the climate observation stations, combinations of land covers and soils, and over 108 years of simulation, in only a tiny fraction of the seasons (<0.1%) was the soil not fully recharged by the beginning of the next start of discharge.

Regionally, positive trends toward a later day of recharge across land covers (with the highest rate of change for the pasture land cover) were found over large portions of Wisconsin. The largest changes in a negative direction (full recharge occurring earlier in the year) were found on the pasture land cover in the far northwest of the study area. Urban and wheat land covers had the lowest rates of change in both a positive and negative direction.

In Watertown, NY, for example, the rate of change is -0.1610 days per year with a Forest land cover with a starting intercept of day 313 (November 9th). By the end of the study period this has changed to day 296 (October 23rd), a relative change of over 2 weeks earlier in the year. In contrast, Viroqua, WI, has a positive rate of change on a pasture land cover of +0.1184 with an intercept of day 321 (November 17th). By the end of the study period this has changed to day 333 (November 29th). The greatest positive rate of change in the study area for the rate of recharge is found on the pasture land cover at Pine River, MN (4.32 μm/(day*year)), the greatest negative rate of change for the rate of recharge is -7.85 μm/(day*year) found on the winter wheat land cover at Delphi, IN and an average across the study region of +0.41 μm/(day*year). As for the day of recharge, the greatest positive rate of change in the study region was found at Fond du

Lac, WI with a rate of +0.137 days/year on a corn land cover, the greatest negative rate of charge was at Pine River, MN on a pasture land cover with a rate of -0.403 days/year. Other commonalities across land covers include a trend towards earlier recharge across much of Michigan and a lower rate of change on the Lake Erie coastline in Ohio as compared to the surrounding areas (Figures 62 to 66).

There is a strong geographical distribution within each land cover, though each one shows a different distribution and scales of the rates of change (Figures 70- 79). For the corn land cover, the rate of recharge during the study period is decreasing. In contrast, the rate of recharge is increasing across Central Michigan and the Upper Peninsula of Michigan along with eastern New York. The relationships between the other rates of change are complex. Percolation and runoff are significantly related to this rate of change, at a 99.98% and 99% confidence rating and a negative relationship with runoff. The change in minimum temperatures also plays a part with a negative relationship of 97.2% confidence rating.

As stated previously, the forest land cover has a long growing season with extended roots able to draw moisture from deep in the soil column. The geographical distributions of the rates of change for this land covers recharge rate are somewhat similar to corn. Positive trends were found across Central Michigan, the Upper Peninsula, and southeastern sections of the region. A large portion of this spatial variability comes from annual precipitation, over a 99% confidence rating. This is from both amount of yearly precipitation change and the amount per event of precipitation change.

For pasture, there was a large decrease in the rate of recharge across the western portion of the study area that generally follows the decrease of precipitation rate. Still, for areas where there was an increase in precipitation such as south-west Michigan, the eastern Upper Peninsula, and the Lake Erie coastline there was still a slight decrease or only a weak increase in the rate of recharge. This is perhaps related to increasing temperatures throughout the year, greater ET rates and increasing plant water usage through the recharge period.

Changes in the rate of recharge for the urban land cover were minor compared to the other land covers. This is mainly due to the impermeability of the surface type making increases in precipitation increase runoff rather than ground recharge. The strongest upwards trends can be seen in northern Wisconsin and the western Upper Peninsula. The strongest downwards trends occur in the southern areas of the study region. For the wheat land cover, there was a pronounced slowing of the recharge rate across almost the entire study region. The only exceptions are the far eastern areas of the region and north-west Michigan.

Soil Moisture Days Trends and Patterns.

One of the more interesting aspects of this study is looking for trends in soil moisture days, which is essentially a summation of the time and magnitude of soil moisture at or above the field capacity threshold.

The rates of change for this variable closely resemble the rates of change for precipitation across the study area (Figure 19). Negative rates of change are seen in Wisconsin, suggesting an overall drying of the soil column, while positive rates of change were observed almost everywhere else. The greatest positive rate of change in across the study region was at Pine River, MN with a pasture land cover (+0.406 SMD/year), while the greatest negative rate of change was found at Viroqua, WI with an urban land cover (-0.148 SMD/year). The average trend change across all land covers and soil types was +0.116 SMD/year. Spatial trends for urban and wheat land covers, which are representative of other land covers are given in Figures 67 and 68.

These changes for the urban surface is somewhat more distinct due to the greater rates of runoff for that cover type which increases the overall sensitivity of soil moisture changes associated with changes in precipitation.

For the wheat land cover the rates of change are more moderate due to increasing ET during the summer. The spatial patterns are similar to the precipitation rates of change with lower amounts in Wisconsin, but still close to 0, with the highest rates over Michigan and the western portions of the study area.

Summary of Yearly Spatial-Temporal Trends in Soil Statistics

In general, the results from this study are similar to those of Karl and Knight (1998), who found large scale increases in precipitation along with an increase in extreme precipitation events in the Great Lakes region. One exception was the state of Wisconsin, were precipitation was observed to decrease. Figure 83 shows a spatial distribution of locations with precipitation trends 95% or greater confidence. In general, it suggests a significant increase in precipitation over the study period. Ranges for these increases are from 0.7 mm/year to 1.7 mm/year.

SUMMARY AND CONCLUSION

Consequences for water usage in the Great Lakes region

The main conclusions that can be drawn from this study can be summarized in the following way:

1. For the thirty-year time frame (1979-2008), precipitation is greatest in the eastern portion (Pennsylvania and New York) of the study area and tends to decrease as you move north-west, with the lowest amounts in Minnesota, the central Upper Peninsula of Michigan, and the north-east portion of the Lower Peninsula of Michigan. Precipitation is increasing across the majority of the Great Lakes region over the time period studied and this has a direct impact on plant available soil moisture across all land covers and soils. The largest trends in precipitation can be found in the state of Michigan with high rates of change in eastern Minnesota, north-eastern Iowa, and south-central Wisconsin. Seasonally, autumn shows the widest range of rates of change with western most areas showing decreasing precipitation and increasing everywhere else in the study region. The summer months show the largest spatial area of increasing precipitation with a reducing amount in the Upper Peninsula of Michigan.
2. For the thirty-year time frame (1979-2008), evapotranspiration has a strong south (highest values) to north (lowest values) spatial trend with higher values moving further northward in the western portion of the study area. Evapotranspiration trends across soils and land covers are generally increasing across the time period studied mainly due to increasing temperatures and precipitation across the Great

Lakes region. The greatest positive trends can be seen on pasture land in Michigan, the greatest negative trends can be seen in forested areas in western Wisconsin and the Upper Peninsula of Michigan, and the smallest rates of change can be seen in the winter wheat land cover. These trends can be attributed to growing season timing and length.

3. For the thirty-year time frame (1979-2008), percolation was strongly tied to the pattern seen for precipitation. Areas of higher precipitation showed rates of higher percolation and areas of lower precipitation showed lower amounts of percolation. Percolation had similar trends no matter the land cover across the study region with positive trends showing an increasing amount of water leaving the soil column. The pattern is closely tied to the rates of change for precipitation.
4. For the thirty-year time frame (1979-2008), runoff was spatially varied greatly with the highest values seen for the pasture land cover on a loamy soil in a north-south line stretching from northern Illinois to the Upper Peninsula of Michigan as well as a gradual increase in an easterly direction. The lowest values for the 30-year period were seen in eastern Michigan and Minnesota. Surface runoff is both closely tied to land cover and precipitation trends. Forest land cover shows no change in runoff and urban sees the largest changes. This rate of change follows closely with precipitation changes as well as the land covers ability to prevent water movement on the surface. This finding could be seen as a predictor of the ability of urban water drainage systems ability to handle storm run-off. It also directly affects soil erosion which can impact bluff and beach erosion (tourism),

loss of top soil (agriculture), and the introduction of fertilizer and other man-made chemicals into the Great Lakes waterways (fisheries).

5. The year to year rates of change of the daily variables shows significant trends almost everywhere. Each of these traits directly impacts the areas of agriculture, forestry and urban water management.
    a. For the 1979-2008 time frame there is a strong south to north trend with the latest Day of Discharges occurring in the northern sections of the study area. The trends for the entire time frame show the day of year when the soil begins to discharge is generally getting earlier in the year from earlier snowmelt from increased temperatures. This occurs across soil and land cover types. The date at which the soil recharges is also moving earlier in the year over much of the study area. Notable exceptions are where the trend for precipitation amounts is negative. When looking at the pasture and urban land covers due to the near constant water use during the warm seasons, one can see this pattern very clearly.
    b. The rate of discharge is based on two variables, both of which are changing. While the beginning of discharge is occurring earlier in the year, the day of minimum plant available soil moisture is also getting earlier across much of the study area. This leads to an increase in the rate of discharge. Areas that have a slower rate of discharge are correlated with areas with a positive precipitation rate of change. The rate of recharge also varied significantly across the study region. Land covers that have a

growing season that extends into the period of where temperatures begin to cool and PET begins to decrease are slowing down the rate of recharge. These patterns can be seen in the corn, pasture, and wheat land covers where a long growing season that is stretching later in the year is and is reducing the rate of recharge.

c. In the 1979-2008 time period, the day of minimum soil moisture shows a similar spatial pattern across all land covers, with a north-east to south-west decreasing (earlier) trend. The day of year where the soil moisture is lowest is also changing across the region as it is affected by both the land cover and the amount and timing of precipitation. It is getting earlier in the year over much of the study area with notable differences between land covers, with the strongest movement towards the beginning of the year often found in Michigan (with a movement of almost 20 days earlier in one case) and the strongest movement towards the end of the year in the south western, western, and Lake Erie areas.

d. The average of the 1979-2008 time period shows a drier soil conditions in the northern areas of the study region and wetter areas in the south for the corn and wheat land cover, while the forest and urban land covers show spatial homogeneity. The minimum amount of soil moisture is increasing in all areas except where there is a negative trend in precipitation. This is an important find as it directly affects the amount of water stress agricultural products will experience without irrigation or the amount of irrigation needed to prevent water stress in the same crop cover.

e. The 1979-2008 time frame shows much less of a spatial trend across the study region for the date at which field capacity was reached in the fall with only a slight trend towards later recharge dates occurring in the northern areas than in the southern areas. The trends for the 1900-2008 show positive trends toward a later day of recharge across land covers (with the highest rate of change for the pasture land cover) were found over large portions of Wisconsin.

f. When examining the 1979-2008 averages of Field Capacity Days, or the integration of the total amount of daily soil moisture in the soil column, shows that the lowest values (driest overall soils) can be found in the central part of the study region, Michigan, Indiana, Illinois, and eastern Wisconsin. Field Capacity Days also show an upwards trend across the study region, only with the notable exceptions of Wisconsin and parts of the western Upper Peninsula of Michigan, but then only slight negative trends. This finding shows that over the course of an entire year during the time frame of this study that soil is getting more wet overall.

All of these soil moisture trends show a different Great Lakes region in the present then even 100 years ago. It shows a Great Lakes region that is slowly getting wetter and warmer. It shows a region where agricultural producers and urban planners have needed to change their policies and ideas about water entering their fields or drainage systems.

Finally it shows that these trends will continue into the future as climate change continues to affect the Great Lakes region.

APPENDICES

	Corn	Forest	Pasture	Urban	Wheat
ET	499.9	570.6	593.3	506.4	476.3
Drainage	311.2	326.4	292.7	80.6	354.9
Runoff	88.9	3.2	14.1	313.1	68.6

Table 1: Soil Moisture variables (mm) averaged across study region and across soil types, 1979-2008.

	S	SL	L	SiL	SiCL	CL
ET	471.6	528.9	540.7	526.6	570.1	537.9
Drainage	343.9	288.6	268.3	266.8	222.5	248.8
Runoff	83.2	82.8	91.5	106.8	107.5	113.6

Table 2: Soil Moisture variables (mm) averaged across study region and across land cover types, 1979-2008.

Station Name	Grid / Observed Annual Precipitation Totals	Grid / Observed Annual Wet Days	Precipitation amount Ratio
Alpena, MI	1.09	1.57	0.69
Ann Arbor, MI	1.08	1.57	0.69
Chicago, IL	1.01	1.87	0.54
Geneva, NY	1.05	1.79	0.59
Grayling, MI	0.94	1.31	0.72
Indiana, PA	0.95	1.73	0.55
Rogers City, MI	1.02	2.08	0.49
Sheboygan, WI	1.04	2.06	0.50
Traverse City, MI	1.02	1.76	0.58
Wilkes Barre, PA	1.16	1.82	0.64

Table 3: Comparison of Precipitation Data from observed precipitation and the associated grid box.

Observation Station	SWAT – Observed PAW	Absolute Value of SWAT – Observed
Bondville, IL	0.65	22.98
Champaign, IL	3.27	26.53
Topeka, IL	5.06	27.24

Table 4: Differences in Simulated and Observed Plant Available Soil Moisture in mm of Plant Available Water.

Soil Name	Clay %	Silt %	Sand %
Sand	5	5	90
Sandy Loam	10	30	60
Loam	20	40	40
Silty Loam	10	60	30
Silty Clay Loam	30	60	10
Clay Loam	35	35	30

Table 5: Composition of Soil Textures used for plant available water comparisons.

Yearly Timeframe	Average Year 95% confidence	Average Year 99% confidence	STDEV Year 95% confidence	STDEV Year 99% confidence	# of stations 95% confidence	# of stations 99% confidence
Full Year	1965	1967	28.25	23.82	18	12
Dec, Jan, Feb	1961	1973	39.85	39.57	10	6
Mar, Apr, May	1957	1934	31.76	N/A	3	1
Jun, Jul, Aug	1958	N/A	42.33	N/A	6	0
Sep, Oct, Nov	1965	1969	28.18	6.18	9	4

Table 6: Precipitation Breakpoints as determined from a SNHT.

Land Cover / Soil Grouping	ET	PERC	REVAP	SURQ
Sand	174.84	110.45	251.56	120.11
Sandy Loam	274.83	68.32	172.68	119.87
Loam	246.00	99.16	154.37	135.85
Silty Loam	197.47	102.09	192.89	233.92
Silty Clay Loam	148.487	96.23	234.87	283.45
Clay Loam	278.88	101.75	384.43	199.21
Corn	38.08	5.42	6.26	2.20
Forest	27.17	6.59	26.74	5.79
Pasture	92.90	8.60	7.43	5.03
Urban	100.12	70.44	102.01	3.69
Wheat	10.33	4.02	5.24	2.61

Table 7: Relative Standard Deviations of soil moisture variables. Soil or Land Cover groupings. ET=Evapotranspiration, PERC=Percolation, REVAP=Return Water from Shallow Aquifer, SURQ=Surface Runoff.

Station	Corn	Forest	Pasture	Urban	Wheat
Ann Arbor, MI	505.0	589.9	601.4	523.4	479.7
Angelica, NY	493.2	543.0	601.8	505.1	463.0
Aurora, IL	520.3	581.7	630.8	528.1	489.4
Big Rapids, MI	487.2	557.9	586.9	499.8	464.5
Cheboygan, MI	452.9	508.8	531.1	450.4	434.6
Clinton, IA	529.2	608.2	644.8	525.1	498.2
Coldwater, MI	518.7	610.9	609.4	533.4	492.5
Delphi, IN	543.4	637.7	672.9	544.1	505.5
Dixon, IL	526.1	614.9	637.9	532.5	497.2
Fond du Lac, WI	490.5	587.2	579.0	486.9	476.7
Farmington, MN	512.9	590.5	604.6	502.0	492.1
Fayette, IA	538.2	597.7	635.6	541.2	506.8
Iron Mountain, MI	431.8	520.7	569.5	471.3	454.9
Ironwood, MI	471.4	529.3	533.7	478.4	453.1
Norwalk, OH	521.4	600.3	624.2	536.3	489.9
Oberlin, OH	516.1	604.6	614.3	532.3	481.6
Oconto, WI	479.0	538.7	584.0	482.4	460.9
Owosso, MI	481.5	523.9	562.1	493.0	465.1
Pine River, MN	483.7	543.6	544.4	474.2	472.6
Portage, WI	521.6	580.0	618.9	525.4	491.6
South Haven, MI	481.4	545.3	566.0	497.6	462.5
Spooner, WI	501.4	553.9	598.6	493.2	479.3
Sault Ste Marie, MI	442.8	498.0	491.6	436.4	415.4
Two Harbors, MN	483.7	557.3	542.9	466.8	469.5
Viroqua, WI	510.1	588.0	600.3	507.9	484.7
Wooster, OH	536.6	621.0	632.1	553.9	497.1
Warren, PA	529.4	586.6	622.4	548.9	493.1
Watertown, NU	478.3	531.5	557.5	495.3	457.3
Wauseon, OH	509.7	597.6	608.3	519.1	483.5

Table 8: Average Annual Simulated Evapotranspiration (mm), 1979-2008, by land cover.

Station	S	SL	L	SiL	SiCL	CL
Ann Arbor, MI	477.6	536.8	550.7	535.6	588.5	550.1
Angelica, NY	472.7	520.5	529.7	520.4	554.5	529.6
Aurora, IL	489.1	549.5	561.6	547.0	593.6	559.5
Big Rapids, MI	457.2	516.0	530.1	515.6	567.7	529.0
Cheboygan, MI	416.9	473.3	486.7	471.4	520.5	484.5
Clinton, IA	500.9	562.4	574.6	557.6	602.5	568.6
Coldwater, MI	491.8	551.7	564.4	550.0	597.1	562.9
Delphi, IN	517.0	581.7	593.6	578.0	624.1	589.9
Dixon, IL	501.5	562.1	574.3	559.6	602.5	570.3
Fond du Lac, WI	463.7	523.9	536.8	520.5	566.9	532.6
Farmington, MN	485.5	543.6	553.2	538.7	574.8	546.9
Fayette, IA	511.0	567.1	576.1	563.8	594.7	570.8
Iron Mountain, MI	436.1	488.3	500.9	486.6	529.0	496.9
Ironwood, MI	440.1	492.3	502.9	491.8	529.9	502.1
Norwalk, OH	494.6	553.3	565.3	551.7	597.5	564.0
Oberlin, OH	488.1	547.8	561.1	546.2	595.6	559.7
Oconto, WI	448.5	508.2	521.3	506.2	551.5	518.4
Owosso, MI	444.8	502.3	516.1	501.1	551.8	514.4
Pine River, MN	452.8	506.5	515.2	501.3	537.1	509.4
Portage, WI	490.6	548.2	560.1	545.8	584.6	555.6
South Haven, MI	446.7	506.2	521.2	504.4	565.2	519.7
Spooner, WI	472.5	527.9	537.9	523.6	558.4	531.4
Sault Ste Marie, MI	400.9	452.5	465.6	452.3	503.7	465.9
Two Harbors, MN	450.3	506.3	515.7	503.4	536.6	512.0
Viroqua, WI	483.8	540.0	550.6	536.9	572.3	545.5
Wooster, OH	508.2	568.1	579.6	566.6	608.0	578.2
Warren, PA	506.6	557.0	565.2	555.6	588.3	563.8
Watertown, NU	446.0	500.8	513.7	500.4	549.6	513.3
Wauseon, OH	482.2	542.5	555.5	540.6	587.6	553.3

Table 9: Average Annual Simulated Evapotranspiration (mm), 1979-2008, by soil texture.

Station	Corn	Forest	Pasture	Urban	Wheat
Ann Arbor, MI	369.5	353.9	335.1	116.1	412.2
Angelica, NY	390.2	430.7	359.0	127.8	442.8
Aurora, IL	324.2	371.5	306.5	76.0	376.5
Big Rapids, MI	339.3	358.8	317.8	95.7	381.2
Cheboygan, MI	253.7	265.6	233.0	69.9	288.6
Clinton, IA	254.9	260.7	214.4	47.8	304.7
Coldwater, MI	348.0	343.2	333.0	91.6	395.0
Delphi, IN	338.6	341.4	295.6	82.9	398.0
Dixon, IL	310.3	334.5	295.8	60.8	364.6
Fond du Lac, WI	208.2	180.2	180.1	35.2	237.9
Farmington, MN	203.6	201.9	180.3	28.3	240.0
Fayette, IA	295.7	350.7	300.2	52.7	351.7
Iron Mountain, MI	246.3	227.8	173.1	39.4	242.8
Ironwood, MI	311.8	358.0	333.0	82.0	355.7
Norwalk, OH	359.6	360.6	329.4	99.9	410.9
Oberlin, OH	363.9	352.5	333.6	105.5	416.3
Oconto, WI	260.1	286.3	229.5	56.0	297.4
Owosso, MI	280.7	298.0	254.3	69.5	311.4
Pine River, MN	174.4	179.8	169.8	20.4	203.4
Portage, WI	281.6	326.2	270.0	52.9	330.4
South Haven, MI	354.3	370.1	338.0	107.2	392.1
Spooner, WI	206.2	226.1	177.0	28.2	245.0
Sault Ste Marie, MI	330.4	345.9	340.6	123.3	376.4
Two Harbors, MN	230.2	225.3	230.3	48.5	263.2
Viroqua, WI	258.0	275.8	252.1	44.6	303.5
Wooster, OH	390.3	393.0	374.6	110.1	451.6
Warren, PA	553.2	608.3	557.5	211.7	619.4
Watertown, NU	481.8	549.4	501.2	182.8	531.3
Wauseon, OH	305.1	289.8	272.9	71.8	348.7

Table 10: Average Annual Simulated Drainage (mm), 1979-2008, by land cover.

Station	S	SL	L	SiL	SiCL	CL
Ann Arbor, MI	394.1	336.1	313.9	312.9	255.8	291.2
Angelica, NY	414.7	367.0	347.7	342.6	305.8	322.9
Aurora, IL	366.9	310.2	286.2	282.5	235.1	264.9
Big Rapids, MI	373.4	315.2	294.1	293.2	243.4	272.1
Cheboygan, MI	289.3	232.8	215.8	219.5	175.4	200.1
Clinton, IA	288.0	230.0	209.0	209.9	167.0	195.1
Coldwater, MI	378.7	320.7	297.7	295.8	244.8	275.2
Delphi, IN	371.4	309.9	286.1	282.4	233.7	264.2
Dixon, IL	348.1	290.4	266.8	264.1	222.3	247.6
Fond du Lac, WI	235.3	178.4	160.3	163.5	122.0	150.3
Farmington, MN	233.6	179.5	162.9	163.6	131.8	153.6
Fayette, IA	338.8	285.6	264.2	259.1	226.3	247.2
Iron Mountain, MI	245.4	195.4	178.9	182.4	145.8	167.3
Ironwood, MI	354.9	301.4	285.3	282.5	245.0	259.4
Norwalk, OH	386.5	329.9	308.2	305.2	256.1	286.5
Oberlin, OH	391.0	332.8	309.9	309.3	255.6	287.7
Oconto, WI	295.0	239.2	219.1	220.6	178.8	202.5
Owosso, MI	314.2	257.6	237.7	239.0	187.6	220.5
Pine River, MN	206.5	155.8	142.3	145.2	113.8	133.7
Portage, WI	322.0	267.7	245.9	243.0	205.7	228.8
South Haven, MI	393.4	337.2	311.1	308.9	239.4	284.0
Spooner, WI	236.4	186.0	168.1	169.3	139.6	159.5
Sault Ste Marie, MI	374.2	320.8	303.1	301.9	244.2	275.6
Two Harbors, MN	263.2	210.3	192.7	191.6	159.7	179.5
Viroqua, WI	293.6	241.1	220.2	218.5	182.0	205.4
Wooster, OH	421.0	363.4	340.4	334.9	287.8	315.9
Warren, PA	584.8	531.6	511.7	499.8	454.8	477.2
Watertown, NU	527.3	468.4	448.7	444.9	391.7	414.6
Wauseon, OH	332.2	275.1	252.1	251.2	202.0	233.4

Table 11: Average Annual Simulated Drainage (mm), 1979-2008, by soil type.

Station	Corn	Forest	Pasture	Urban	Wheat
Ann Arbor, MI	70.5	1.2	8.2	305.2	53.1
Angelica, NY	92.6	1.9	14.7	342.2	70.1
Aurora, IL	115.1	6.0	22.0	355.6	93.6
Big Rapids, MI	94.6	4.4	16.4	326.1	75.3
Cheboygan, MI	68.6	1.7	11.4	255.1	51.9
Clinton, IA	86.7	2.5	11.0	299.2	67.9
Coldwater, MI	90.7	3.2	14.7	332.2	69.9
Delphi, IN	99.4	2.2	12.9	354.9	77.9
Dixon, IL	120.3	4.6	20.9	363.2	94.5
Fond du Lac, WI	66.5	1.0	8.2	245.0	50.4
Farmington, MN	75.8	1.9	8.5	262.3	59.3
Fayette, IA	121.5	5.7	19.5	362.4	96.6
Iron Mountain, MI	71.5	2.2	10.0	240.7	51.4
Ironwood, MI	111.0	6.1	26.8	332.3	85.2
Norwalk, OH	81.6	1.6	8.9	326.0	61.8
Oberlin, OH	78.3	1.1	9.0	318.8	60.3
Oconto, WI	86.7	2.6	13.1	289.0	66.9
Owosso, MI	61.9	1.0	7.4	261.2	47.7
Pine River, MN	65.8	1.6	9.0	227.4	47.7
Portage, WI	107.6	6.5	21.8	334.5	88.6
South Haven, MI	86.0	6.1	17.6	317.1	67.1
Spooner, WI	74.1	1.9	8.4	260.7	56.9
Sault Ste Marie, MI	75.7	4.0	15.9	290.2	57.0
Two Harbors, MN	70.1	1.2	10.6	267.9	51.2
Viroqua, WI	101.1	6.9	18.4	317.0	80.8
Wooster, OH	88.8	1.7	9.1	351.8	67.0
Warren, PA	114.5	2.9	17.6	436.2	84.6
Watertown, NU	127.6	7.2	29.4	409.1	99.1
Wauseon, OH	73.8	0.5	6.9	297.4	56.4

Table 12: Average Annual Simulated Runoff (mm), 1979-2008, by land cover.

Station	S	SL	L	SiL	SiCL	CL
Ann Arbor, MI	72.2	72.3	80.6	96.7	100.2	103.9
Angelica, NY	86.9	88.3	98.8	113.6	114.5	123.7
Aurora, IL	102.7	100.2	112.2	130.1	130.5	135.1
Big Rapids, MI	89.7	90.3	97.4	112.7	110.1	120.1
Cheboygan, MI	68.2	69.5	73.2	84.6	79.9	91.0
Clinton, IA	81.1	79.0	87.9	103.8	101.5	107.5
Coldwater, MI	85.8	85.3	95.5	111.8	114.9	119.5
Delphi, IN	91.7	90.0	102.0	121.4	123.8	127.7
Dixon, IL	104.9	102.9	114.4	132.1	131.5	138.2
Fond du Lac, WI	65.7	64.5	70.0	82.7	78.4	84.2
Farmington, MN	71.8	69.6	77.0	90.4	88.0	92.6
Fayette, IA	104.2	102.9	115.4	132.7	134.2	137.5
Iron Mountain, MI	66.8	67.0	71.4	81.5	77.4	86.8
Ironwood, MI	97.7	100.0	105.5	119.4	118.9	132.2
Norwalk, OH	80.0	79.4	89.2	105.9	109.0	112.3
Oberlin, OH	77.9	77.5	86.8	102.7	105.7	110.4
Oconto, WI	81.0	79.4	86.5	99.9	97.4	105.9
Owosso, MI	64.3	64.4	70.3	84.1	83.0	88.9
Pine River, MN	63.4	61.2	66.2	77.1	73.2	80.7
Portage, WI	96.8	95.6	106.1	122.7	121.9	127.5
South Haven, MI	81.0	78.9	90.1	108.5	116.3	117.8
Spooner, WI	71.6	68.4	76.4	89.2	85.3	91.3
Sault Ste Marie, MI	72.2	74.7	80.7	94.9	101.0	107.6
Two Harbors, MN	69.3	67.2	75.5	88.9	87.7	92.5
Viroqua, WI	90.6	88.8	99.5	114.6	116.2	119.4
Wooster, OH	85.0	84.3	96.0	114.7	120.1	122.1
Warren, PA	104.4	108.9	120.7	142.2	154.2	156.5
Watertown, NU	113.3	119.0	125.9	142.8	146.0	159.8
Wauseon, OH	73.2	71.1	81.0	96.9	98.0	101.7

Table 13: Average Annual Simulated Runoff (mm), 1979-2008, by soil texture.

Climate Station	Soil Attribute	All Soils	S	SL	L	SiL	SiCL	CL	SL, L, and SiL	Relative STDEV All Soils	Relative STDEV SL, L, SiL
Ann Arbor, MI	ET	0.34[1]	0.30[1]	0.32[1]	0.32[1]	0.34[1]	0.39[2]	0.36[1]	0.33[1]	8.96	3.18
	PERC	1.18[3]	1.21[3]	1.22[3]	1.21[3]	1.16[3]	1.15[3]	1.12[3]	1.19[3]	3.48	2.82
	REVAP	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.01	36.89	27.54
	SURQ	0.18	0.12	0.14	0.16	0.19	0.25[1]	0.22	0.16	28.57	17.76
Clinton, IA	ET	-0.06	-0.05	-0.06	-0.07	-0.07	-0.01	-0.08	-0.07	44.71	2.72
	PERC	-0.06	-0.09	-0.05	-0.06	-0.06	-0.06	-0.06	-0.06	23.43	7.95
	REVAP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	233.48	196.16
	SURQ	-0.12	-0.10	-0.12	-0.11	-0.12	-0.12	-0.12	-0.12	7.57	7.45
Two Harbors, MN	ET	0.26[1]	0.21	0.26[1]	0.26[1]	0.27[1]	0.26[2]	0.27[2]	0.26[1]	9.25	1.15
	PERC	0.92[3]	1.03[3]	0.98[3]	0.92[3]	0.86[3]	0.89[3]	0.87[3]	0.92[3]	7.22	6.53
	REVAP	0.02[1]	0.02[1]	0.02[1]	0.02[1]	0.02[1]	0.02[2]	0.02[1]	0.02[1]	13.40	4.38
	SURQ	0.24[2]	0.18[1]	0.18[2]	0.23[2]	0.26[2]	0.29[2]	0.28[2]	0.22[2]	20.09	18.39
Viroqua, WI	ET	-0.19	-0.22	-0.24	-0.19	-0.20	-0.10	-0.17	-0.21	25.68	12.36
	PERC	0.01	-0.01	0.04	0.02	0.03	-0.02	0.02	0.03	169.57	38.95
	REVAP	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	279.64	28.93
	SURQ	-0.02	-0.01	-0.03	-0.01	-0.02	-0.01	-0.02	-0.02	53.78	44.95
Watertown, NY	ET	0.02	0.01	0.02	0.01	0.02	0.05	0.01	0.02	89.37	20.65
	PERC	0.91[3]	0.93[3]	0.99[3]	0.93[3]	0.89[3]	0.85[3]	0.88[3]	0.94[3]	5.48	5.44
	REVAP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	53.44	30.00
	SURQ	0.15	0.12	0.11	0.15	0.15	0.20[1]	0.17	0.14	22.80	16.26

Table 14: Rate of change (mm/year) of yearly soil attributes, selected climate stations, comparison of soil textures. [1]0.95 confidence, [2]0.99 confidence, [3]0.999 confidence

Climate Station	Change in Precipitation (mm / year)
Ann Arbor, MI	1.68[3]
Clinton, IA	-0.34
Two Harbors, MN	1.50[3]
Viroqua, WI	-0.20
Watertown, NY	1.22[2]

Table 15: Change in annual Precipitation trends (mm/year) for selected climate stations: 1900-2008. [1]0.95 confidence, [2]0.99 confidence, [3]0.999 confidence.

Station Name	Land Cover	ET	ET Slope	Drainage	Drainage Slope	Runoff	Runoff Slope
Ann Arbor, MI	Corn	512.90	0.31	361.53	1.24	70.90	0.14
	Forest	586.53	0.25	358.00	1.27	0.77	0.00
	Pasture	598.84	0.50	338.78	1.22	7.70	0.01
	Urban	528.04	0.38	133.32	0.81	283.51	0.56
	Wheat	478.78	0.19	413.32	1.42	53.22	0.12
Clinton, IA	Corn	537.80	-0.01	245.71	-0.07	87.64	-0.17
	Forest	605.35	-0.17	263.77	0.08	2.19	0.00
	Pasture	643.53	-0.09	216.55	-0.26	10.85	-0.01
	Urban	540.55	0.05	49.37	-0.01	282.57	-0.27
	Wheat	497.06	-0.11	306.07	-0.02	67.97	-0.13
Two Harbor, MN	Corn	492.43	0.24	221.12	0.97	70.60	0.25
	Forest	558.32	0.27	224.65	1.14	0.91	0.00
	Pasture	543.61	0.21	230.19	1.26	10.17	0.04
	Urban	478.58	0.40	51.75	0.22	252.90	0.65
	Wheat	469.38	0.20	263.29	1.00	51.47	0.18
Viroqua, WI	Corn	519.21	-0.10	249.32	-0.08	100.88	0.00
	Forest	587.40	-0.38	277.74	0.23	5.74	0.00
	Pasture	599.30	-0.40	254.59	0.15	17.00	0.00
	Urban	522.49	-0.05	46.04	-0.04	301.31	-0.09
	Wheat	484.03	-0.12	305.42	-0.09	79.77	-0.01
Watertown, NY	Corn	485.54	0.05	473.33	0.96	129.11	0.14
	Forest	530.37	0.05	553.04	1.07	5.25	0.00
	Pasture	554.04	-0.10	506.45	1.10	27.97	0.05
	Urban	498.06	0.06	205.53	0.61	384.29	0.38
	Wheat	456.69	0.02	531.84	0.94	99.56	0.11

Table 16: 30-year average (1979-2008) annual hydrology variables (mm) and associated rate of change (mm/year) by land cover for selected stations.

Station Name	Land Cover	DOY Start of Discharge	SoD Slope	DOY Min SW	DoY Min SW Slope	Min SW (mm)	Min SW Slope
Ann Arbor, MI	Corn	43.3	-0.10	188.2	-0.11	72.0	0.09
	Forest	43.9	-0.18	210.0	0.00	35.8	0.03
	Pasture	45.3	-0.10	218.6	-0.11	33.7	0.03
	Urban	44.6	-0.18	242.5	0.01	45.9	0.04
	Wheat	45.4	-0.06	180.3	0.02	129.4	0.17
Clinton, IA	Corn	45.9	-0.05	142.3	-0.04	80.1	-0.04
	Forest	54.5	-0.03	155.4	0.00	41.1	-0.02
	Pasture	50.6	-0.08	170.1	0.04	40.4	0.02
	Urban	59.7	-0.04	182.5	-0.01	39.5	-0.01
	Wheat	46.1	-0.08	139.7	-0.04	124.2	0.05
Two Harbor, MN	Corn	52.9	-0.10	181.8	0.00	54.4	0.04
	Forest	59.9	-0.05	184.9	-0.04	43.9	0.03
	Pasture	52.3	-0.14	184.4	-0.04	80.4	0.20
	Urban	64.4	-0.12	182.6	-0.02	62.8	0.04
	Wheat	50.5	-0.03	132.6	0.00	88.7	0.16
Viroqua, WI	Corn	54.9	0.01	157.1	0.00	72.3	-0.18
	Forest	65.9	0.07	167.8	-0.08	47.8	0.00
	Pasture	61.9	0.08	179.1	-0.01	44.9	0.00
	Urban	74.6	0.10	190.4	0.04	58.0	0.03
	Wheat	55.2	0.02	132.9	0.01	121.3	0.03
Watertown, NY	Corn	48.0	-0.04	159.2	0.00	63.7	-0.06
	Forest	46.3	-0.07	166.4	0.00	37.9	-0.02
	Pasture	46.9	-0.07	177.5	-0.02	35.6	-0.01
	Urban	46.2	-0.06	179.7	-0.07	57.5	-0.01
	Wheat	45.6	-0.08	134.6	0.01	117.3	-0.02

Table 17a: 30-year average (1979-2008) inter-annual hydrology variables and associated rate of change by land cover for selected stations.

Station Name	Land Cover	End of Recharge	EoD Slope	Field Capacity Days	Field Capacity Days Slope
Ann Arbor, MI	Corn	305.7	-0.16	318.8	0.18
	Forest	430.6	-0.19	279.6	0.27
	Pasture	458.7	-0.18	280.7	0.17
	Urban	412.1	-0.08	265.3	0.33
	Wheat	490.2	-0.12	340.1	0.13
Clinton, IA	Corn	309.0	0.03	319.3	0.01
	Forest	334.8	0.11	281.4	-0.03
	Pasture	343.1	0.08	277.6	-0.03
	Urban	396.0	0.00	248.3	-0.02
	Wheat	294.7	0.00	334.3	0.00
Two Harbor, MN	Corn	322.7	-0.09	319.7	0.14
	Forest	340.0	-0.15	295.4	0.19
	Pasture	324.9	-0.08	317.5	0.33
	Urban	383.0	-0.01	273.5	0.36
	Wheat	288.4	-0.10	329.7	0.17
Viroqua, WI	Corn	295.9	0.01	323.9	-0.03
	Forest	314.9	0.01	296.5	0.03
	Pasture	328.9	0.12	294.5	-0.05
	Urban	394.3	0.00	254.6	-0.15
	Wheat	280.1	0.00	337.3	0.01
Watertown, NY	Corn	298.3	-0.05	317.8	0.02
	Forest	298.0	-0.16	297.0	0.11
	Pasture	309.0	-0.15	292.1	0.12
	Urban	341.8	-0.11	285.6	0.11
	Wheat	280.2	0.01	337.7	0.02

Table 17b: 30-year average (1979-2008) inter-annual hydrology variables and associated rate of change by land cover for selected stations.

Climate Station	Land Cover	ET trends average of all soils (mm/year)	ET trends for average of SL, L, and SiL (mm/year)
Ann Arbor, MI	Corn	0.30[1]	0.31[1]
	Forest	0.25	0.25
	Pasture	0.47[1]	0.50[1]
	Urban	0.48[2]	0.38[1]
	Wheat	0.19	0.19
Clinton, IA	Corn	0.01	-0.01
	Forest	-0.15	-0.17
	Pasture	-0.08	-0.09
	Urban	0.05	0.05
	Wheat	-0.10	-0.11
Two Harbor, MN	Corn	0.22[2]	0.24[2]
	Forest	0.24	0.27
	Pasture	0.21	0.21
	Urban	0.41[3]	0.40[3]
	Wheat	0.20[1]	0.20[1]
Viroqua, WI	Corn	-0.07	-0.10
	Forest	-0.37	-0.38
	Pasture	-0.35	-0.40
	Urban	-0.05	-0.05
	Wheat	-0.10	-0.12
Watertown, NY	Corn	0.04	0.05
	Forest	0.05	0.05
	Pasture	-0.08	-0.10
	Urban	0.07	0.06
	Wheat	0.02	0.02

Table 18: Slopes of annual evapotranspiration trends, different land covers of selected stations (mm/year). [1]0.95 confidence, [2]0.99 confidence, [3]0.999 confidence

Climate Station	Land Cover	Percolation trends for all soils (mm/year)	Percolation trends for SL, L, and SiL (mm/year)
Ann Arbor, MI	Corn	1.27[3]	1.24[3]
	Forest	1.33[3]	1.27[3]
	Pasture	1.25[3]	1.22[3]
	Urban	0.60[3]	0.81[3]
	Wheat	1.43[3]	1.42[3]
Clinton, IA	Corn	-0.08	-0.07
	Forest	0.07	0.08
	Pasture	-0.25	-0.26
	Urban	-0.01	-0.01
	Wheat	-0.03	-0.02
Two Harbor, MN	Corn	0.99[3]	0.97[3]
	Forest	1.15[3]	1.14[3]
	Pasture	1.25[3]	1.26[3]
	Urban	0.21[3]	0.22[3]
	Wheat	1.01[3]	1.00[3]
Viroqua, WI	Corn	-0.10	-0.08
	Forest	0.20	0.23
	Pasture	0.12	0.15
	Urban	-0.04	-0.04
	Wheat	-0.11	-0.09
Watertown, NY	Corn	0.93[3]	0.96[3]
	Forest	1.08[2]	1.07[2]
	Pasture	1.08[3]	1.10[3]
	Urban	0.54[3]	0.61[3]
	Wheat	0.92[3]	0.94[3]

Table 19: Slopes of annual percolation trends, different land covers of selected stations (mm/year). [1]0.95 confidence, [2]0.99 confidence, [3]0.999 confidence

Climate Station	Land Cover	Water return trends for all soils (mm/year)	Water return trends for SL, L, and SiL (mm/year)
Ann Arbor, MI	Corn	0.002	0.003
	Forest	0.001	-0.003
	Pasture	-0.002	-0.004
	Urban	0.008[2]	0.009[1]
	Wheat	0.021	0.021
Clinton, IA	Corn	-0.002	-0.004
	Forest	-0.007	-0.008
	Pasture	-0.000	0.002
	Urban	0.002	0.003
	Wheat	0.004	0.004
Two Harbor, MN	Corn	0.016[1]	0.016[1]
	Forest	0.025[1]	0.023[1]
	Pasture	0.023[1]	0.023[1]
	Urban	0.010[2]	0.011[1]
	Wheat	0.021	0.020
Viroqua, WI	Corn	0.001	0.002
	Forest	0.006	0.008
	Pasture	0.005	0.006
	Urban	0.001	0.001
	Wheat	-0.007	-0.006
Watertown, NY	Corn	-0.001	-0.000
	Forest	-0.004	-0.005
	Pasture	-0.002	-0.002
	Urban	-0.001	-0.002
	Wheat	-0.005	-0.005

Table 20: Slopes of annual water return trends, different land covers of selected stations. (mm/year). [1]0.95 confidence, [2]0.99 confidence, [3]0.999 confidence

Climate Station	Land Cover	All soils (mm/year)	SL, L, and SiL (mm/year)
Ann Arbor, MI	Corn	0.14	0.14
	Forest	0.00	0.00
	Pasture	0.01	0.01
	Urban	0.63[1]	0.56[1]
	Wheat	0.12	0.12
Clinton, IA	Corn	-0.16	-0.17
	Forest	0.00	0.00
	Pasture	-0.01	-0.01
	Urban	-0.28	-0.27
	Wheat	-0.12	-0.13
Two Harbor, MN	Corn	0.25[2]	0.25[1]
	Forest	0.00	0.00
	Pasture	0.04[1]	0.04[1]
	Urban	0.70[2]	0.65[2]
	Wheat	0.19[1]	0.18[1]
Viroqua, WI	Corn	0.01	0.00
	Forest	0.00[1]	0.00
	Pasture	0.00	0.00
	Urban	0.10	-0.09
	Wheat	0.01	-0.01
Watertown, NY	Corn	0.15	0.14
	Forest	0.00	0.00
	Pasture	0.05	0.05
	Urban	0.42[1]	0.38[1]
	Wheat	0.12	0.11

Table 21: Slopes of Annual Runoff trends, different land covers of selected stations (mm/year). [1]0.95 confidence, [2]0.99 confidence, [3]0.999 confidence

Climate Station	Land Cover	Day of Discharge	Discharge Rate µm/day	Day of Minimum Soil Water	Minimum Soil Water Amount mm	Recharge Rate µm/day	Day of Recharge[1]	Field Capacity Days
Ann Arbor, MI	Corn	52.83	-0.95	194.65	52.96	1.07	325.42	298.60
	Forest	60.59	-1.06	201.33	26.33	1.09	360.29	247.09
	Pasture	56.08	-0.97	224.65	25.74	1.14	356.03	258.54
	Urban	64.04	-0.86	246.47	32.91	0.98	409.77	225.93
	Wheat	60.59	-1.06	201.33	26.33	1.09	360.29	326.58
Clinton, IA	Corn	48.69	-0.79	182.36	80.77	1.22	288.90	321.05
	Forest	54.33	-1.00	192.19	30.92	1.24	314.92	286.73
	Pasture	56.58	-1.04	208.46	27.05	1.32	330.31	283.20
	Urban	66.61	-0.83	241.40	35.10	0.99	404.67	249.20
	Wheat	50.90	-0.54	168.34	121.23	1.03	268.84	337.25
Two Harbors, MN	Corn	68.56	-0.83	222.67	50.12	1.63	321.34	310.39
	Forest	71.10	-0.95	234.45	31.38	1.25	353.21	279.34
	Pasture	72.54	-0.770	238.43	67.59	1.08	328.09	292.45
	Urban	84.68	-0.84	240.80	56.51	0.83	412.57	237.64
	Wheat	62.79	-1.17	161.79	77.17	1.07	285.32	316.11
Viroqua, WI	Corn	53.96	-0.74	194.33	86.20	1.58	294.12	326.97
	Forest	54.63	-0.90	209.16	32.97	1.58	313.50	292.76
	Pasture	54.61	-0.90	225.85	32.25	1.78	321.08	292.87
	Urban	71.58	-0.81	241.40	47.01	0.87	412.67	261.88
	Wheat	53.75	-0.73	147.56	121.99	0.84	271.83	338.34
Watertown, NY	Corn	51.26	-0.86	196.00	58.80	1.40	297.68	314.76
	Forest	52.11	-0.98	206.16	30.79	1.55	313.08	286.56
	Pasture	52.35	-0.92	226.31	29.89	1.73	321.85	277.85
	Urban	52.37	-0.72	243.79	47.19	1.28	347.29	272.32
	Wheat	53.20	-0.65	153.93	123.98	0.71	267.01	338.19

Table 22: Intercepts of regression trends of Inter-annual soil moisture variables, different land covers of selected stations. Average of SL, L, SiL soil type. [1]When this value is above 365, it means that the recharge date is in the next year.

Climate Station	Land Cover	Date of Discharge days/year	Discharge Rate µm/(days*year)	Date of Minimum Soil Water days/year	Minimum Soil Water Amount (mm/year)	Recharge Rate µm/(days*year)	Date of Recharge days/year	Field Capacity Days days/year
Ann Arbor, MI	Corn	-0.10	0.50	-0.11[1]	0.09	2.10	-0.16	0.18
	Forest	-0.18[2]	0.94	0.00	0.03	3.54	-0.19	0.27
	Pasture	-0.10	0.19	-0.11	0.03	2.85	-0.18	0.17
	Urban	-0.18[1]	1.02	0.01	0.04	0.94	-0.08	0.33
	Wheat	-0.06	1.95[1]	0.02	0.17[2]	-0.03	-0.12	0.13
Clinton, IA	Corn	-0.05	-0.25	-0.04	-0.04	-0.45	0.03	0.01
	Forest	-0.03	-0.32	0.00	-0.02	-0.21	0.11	-0.03
	Pasture	-0.08	0.77	0.04	0.02	0.37	0.08	-0.03
	Urban	-0.04	-0.12	-0.01	-0.01	0.13	0.00	-0.02
	Wheat	-0.08	0.45	-0.04	0.05	-6.47	0.00	0.00
Two Harbors, MN	Corn	-0.10	0.59	0.00	0.04	0.72	-0.09	0.14
	Forest	-0.05	0.41	-0.04	0.03	-1.42	-0.15	0.19
	Pasture	-0.14[1]	1.28	-0.04	0.20[1]	1.42	-0.08	0.33
	Urban	-0.12	0.86	-0.02	0.04	0.18	-0.01[1]	0.36
	Wheat	-0.03	2.28	0.00	0.16	0.39	-0.10	0.17
Viroqua, WI	Corn	0.01	-1.26	0.00	-0.18	-0.58	0.01	-0.03
	Forest	0.07	-1.86	-0.08	0.00	-1.24	0.01	0.03
	Pasture	0.08[1]	-0.46	-0.01	0.00	-4.64	0.12	-0.05
	Urban	0.10	-0.59	0.04	0.03	0.20	0.00	-0.15
	Wheat	0.02	0.38	0.01	0.03	-2.04	0.00	0.01
Watertown, NY	Corn	-0.04	-0.25	0.00	-0.06	2.04	-0.05	0.02
	Forest	-0.07	0.32	0.00	-0.02	2.93	-0.16	0.11
	Pasture	-0.07	0.50	-0.02	-0.01	2.73	-0.15	0.12
	Urban	-0.06	0.06	-0.07	-0.01	1.34	-0.11	0.11
	Wheat	-0.08	0.47	0.01	-0.02	1.54	0.01	0.02

Table 23: Slopes of trends of Inter-annual soil moisture variables, different land covers of selected stations. Average of SL, L, SiL soil type. [1]0.95 confidence, [2]0.99 confidence, [3]0.999 confidence

Climate Station	Land Cover	Sand	Sandy Loam	Loam	Silty Loam	Silty Clay Loam	Clay Loam	Average
Ann Arbor, MI	Corn	1.28	1.13	1.11	1.18	1.31	1.15	1.19
	Forest	1.23	1.38	1.38	1.36	1.72	1.41	1.41
	Pasture	1.26	1.28	1.37	1.31	1.88	1.41	1.42
	Urban	1.22	1.56	1.90	1.93	2.51	2.21	1.89
	Wheat	1.72	1.65	1.59	1.60	1.61	1.57	1.62
Clinton, IA	Corn	1.36	1.31	1.32	1.31	1.35	1.33	1.33
	Forest	1.33	1.57	1.59	1.56	1.93	1.61	1.60
	Pasture	1.49	1.53	1.66	1.51	2.00	1.60	1.63
	Urban	1.39	1.74	2.00	2.21	3.00	2.47	2.13
	Wheat	1.85	1.80	1.79	1.82	1.70	1.80	1.79
Two Harbors, MN	Corn	1.51	1.60	1.58	1.57	1.74	1.59	1.60
	Forest	1.78	1.79	1.87	1.81	2.45	1.91	1.93
	Pasture	1.82	2.06	2.07	2.03	2.36	2.15	2.08
	Urban	1.84	2.32	2.38	2.54	3.03	2.86	2.50
	Wheat	1.59	1.47	1.43	1.48	1.49	1.47	1.49
Viroqua, WI	Corn	1.40	1.38	1.33	1.36	1.46	1.37	1.38
	Forest	1.51	1.70	1.80	1.73	2.09	1.79	1.77
	Pasture	1.46	1.50	1.51	1.50	1.78	1.57	1.55
	Urban	1.64	2.04	2.42	2.51	2.88	2.62	2.35
	Wheat	1.63	1.66	1.56	1.61	1.70	1.65	1.64
Watertown, NY	Corn	1.42	1.27	1.16	1.26	1.18	1.19	1.25
	Forest	1.63	1.35	1.32	1.36	1.27	1.31	1.37
	Pasture	1.57	1.37	1.23	1.29	1.18	1.25	1.31
	Urban	1.38	1.26	1.17	1.23	1.96	1.37	1.40
	Wheat	1.86	1.64	1.53	1.62	1.55	1.6	1.63
	Average	1.53	1.57	1.60	1.63	1.88	1.69	*

Table 24: Temporal Scale, in months, of plant available soil moisture. Selected stations. All soils and land covers.

Station	Average Temperature	Maximum Temperature	Minimum Temperature
Ann Arbor, MI	0.013	0.012	0.014
Angelica, NY	-0.005	-0.008	-0.003
Aurora, IL	0.006	0.004	0.007
Big Rapids, MI	0.002	0.007	-0.003
Cheboygan, MI	0.001	-0.008	0.009
Clinton, IA	0.006	-0.001	0.013
Coldwater, MI	-0.007	-0.014	-0.001
Delphi, IN	0.004	-0.004	0.014
Dixon, IL	-0.002	-0.007	0.004
Fond du Lac, WI	0.001	-0.011	0.014
Farmington, MN	0.011	0.005	0.017
Fayette, IA	-0.001	-0.002	-0.002
Iron Mountain, MI	0.001	0.005	-0.002
Ironwood, MI	-0.004	-0.002	-0.008
Norwalk, OH	-0.004	-0.014	0.007
Oberlin, OH	-0.003	-0.006	0.003
Oconto, WI	-0.004	-0.002	-0.005
Owosso, MI	-0.005	-0.011	0.002
Pine River, MN	0.015	0.013	0.016
Portage, WI	-0.004	-0.001	-0.004
South Haven, MI	0.015	0.008	0.022
Spooner, WI	0.013	0.012	0.014
Sault Ste Marie, MI	0.004	0.011	-0.002
Two Harbors, MN	0.007	-0.004	0.020
Viroqua, WI	-0.005	0.000	-0.009
Wooster, OH	-0.004	-0.014	0.007
Warren, PA	0.004	0.000	0.009
Watertown, NU	0.000	-0.002	0.003
Wauseon, OH	0.002	0.000	0.005
Spearmans[1]	0.02	0.04	0.08
Spearmans[2]	0.31	2.0e-5	6.7e-7
Spearmans[3]	1.4e-3	5.8e-4	0.03
Spearmans[4]	0.39	0.75	0.16
Spearmans[5]	0.93	0.39	0.76
Spearmans[6]	0.18	0.06	0.44
Spearmans[7]	0.73	0.98	0.25

Table 25: Rate of Change of Yearly Average Temperatures (^{o}C / year). Spearmans r_s level of significance [1]Rate of Change of the Beginning Date of Discharge. All observation stations.

[2]Rate of Change of Discharge Rate. [3]Rate of Change of Day of Minimum Soil Moisture. [4]Rate of Change of Minimum Soil Moisture. [5]Rate of Change of Recharge Rate. [6]Rate of Change of Day of End of Recharge. [7]Rate of Change of Field Capacity Days.

Station	Precipitation			Level of Significance
Ann Arbor, MI	1.68		Spearmans[1]	0.037
Angelica, NY	0.82		Spearmans[2]	5.2e-5
Aurora, IL	1.14		Spearmans[3]	0.410
Big Rapids, MI	1.12		Spearmans[4]	2.5e-4
Cheboygan, MI	0.68		Spearmans[5]	0.033
Clinton, IA	-0.34		Spearmans[6]	1.5e-3
Coldwater, MI	1.15		Spearmans[7]	1.8e-4
Delphi, IN	0.28			
Dixon, IL	1.20			
Fond du Lac, WI	-0.28			
Farmington, MN	0.88			
Fayette, IA	1.00			
Iron Mountain, MI	0.13			
Ironwood, MI	0.58			
Norwalk, OH	0.70			
Oberlin, OH	0.53			
Oconto, WI	-0.25			
Owosso, MI	0.75			
Pine River, MN	0.97			
Portage, WI	1.19			
South Haven, MI	0.71			
Spooner, WI	0.37			
Sault Ste Marie, MI	1.74			
Two Harbors, MN	1.50			
Viroqua, WI	-0.20			
Wooster, OH	1.31			
Warren, PA	1.22			
Watertown, NY	0.87			
Wauseon, OH	-0.20			

Table 26: Rate of Change of Yearly Precipitation (mm/ year). Spearmans r_s level of significance [1]Rate of Change of the Beginning Date of Discharge. All observation stations. [2]Rate of Change of Discharge Rate. [3]Rate of Change of Day of Minimum Soil Moisture. [4]Rate of Change of Minimum Soil Moisture. [5]Rate of Change of Recharge Rate. [6]Rate of Change of Day of End of Recharge. [7]Rate of Change of Field Capacity Days

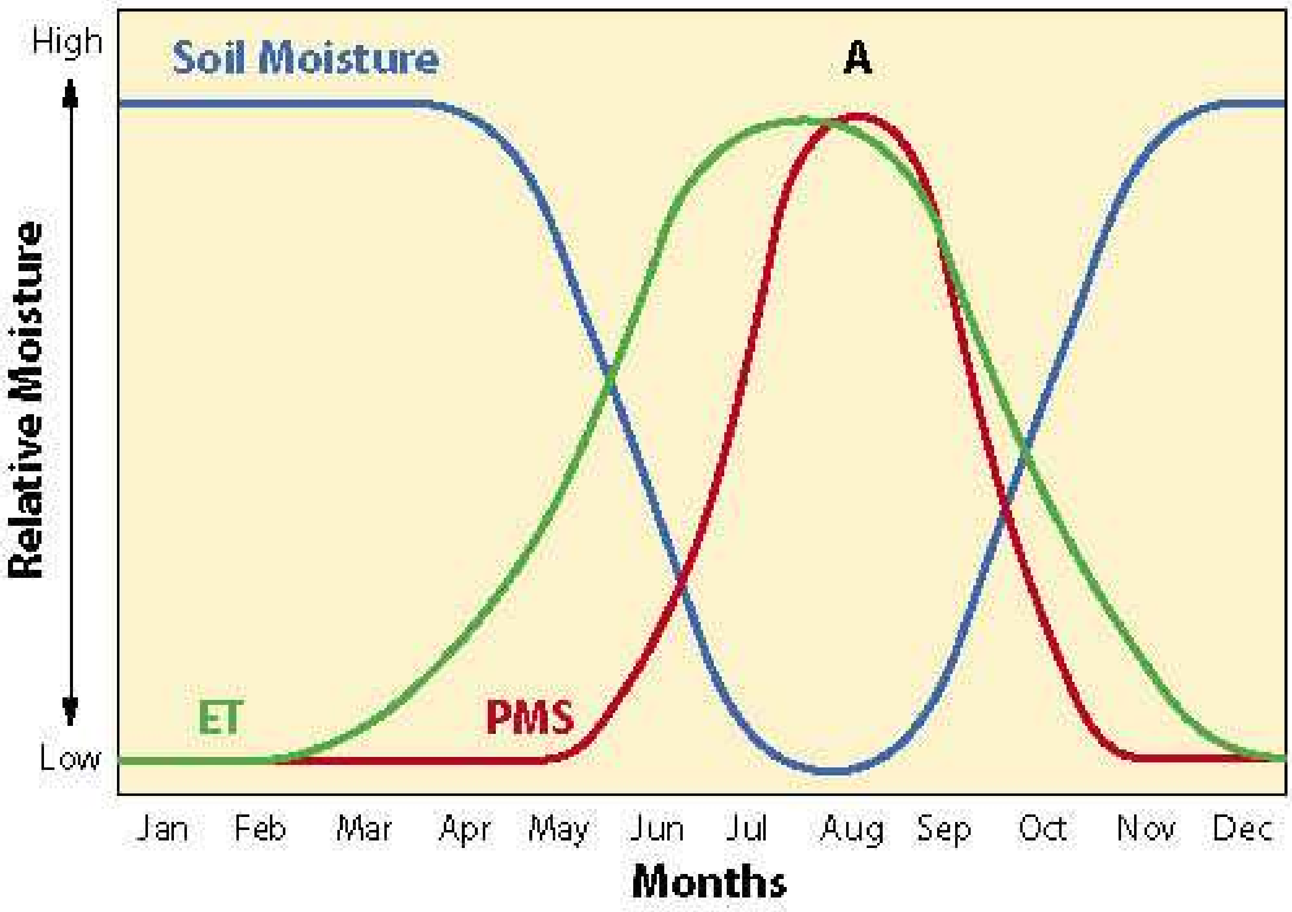

Figure 1: An idealized annual soil moisture curve showing relative levels of soil moisture, Evapotranspiration (ET), and Potential Plant Moisture Stress (PMS). Taken from Roadside Revegetation: An Integrated Approach to Establishing Native Planets. Chapter 5, Figure 5.22. For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this thesis.

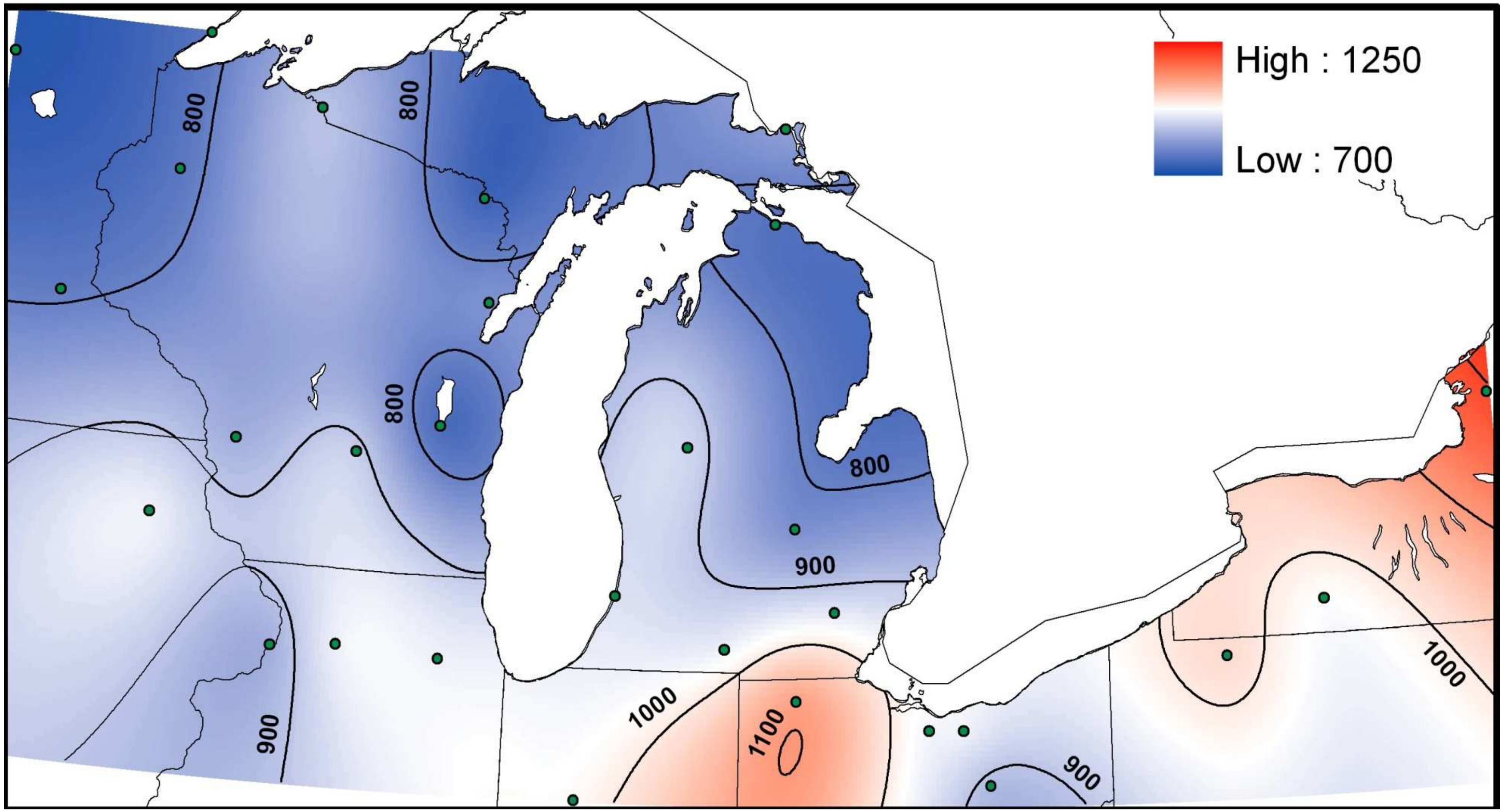

Figure 2: Average Annual precipitation (mm) from 1979-2008 across the study region.

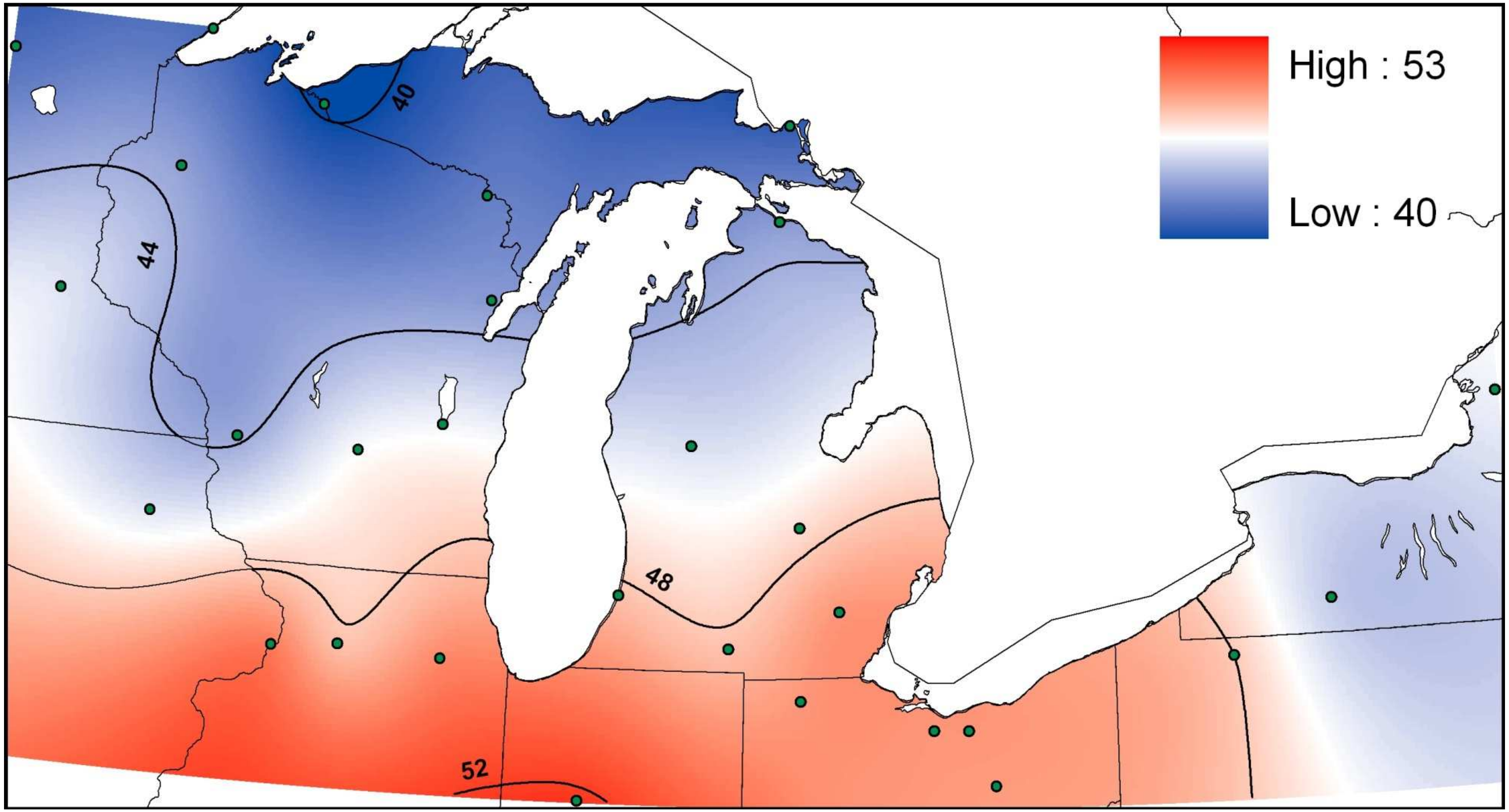

Figure 3: Average Annual Temperatures (F) from 1979-2008 across the study region.

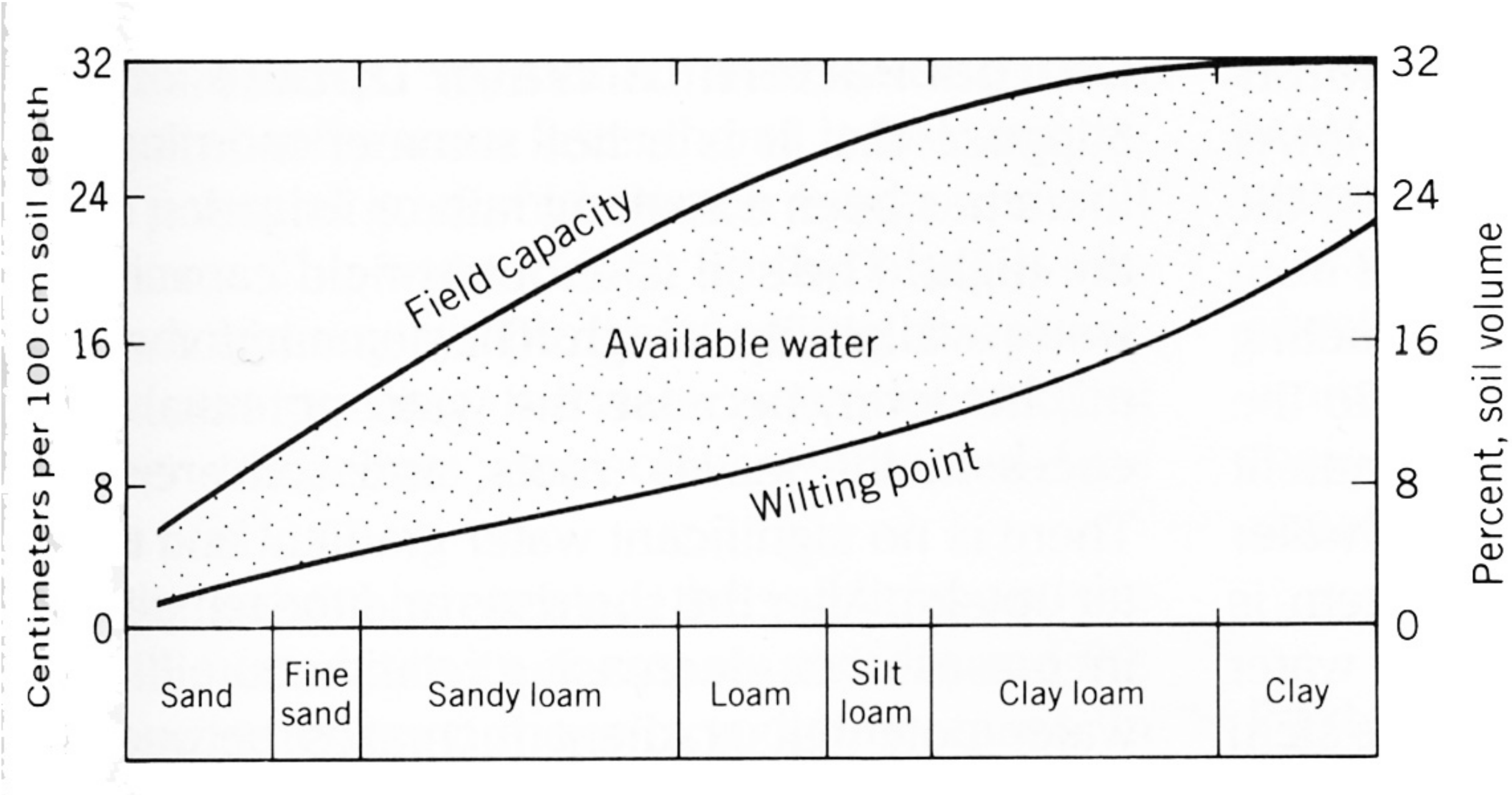

Figure 4: Water Holding Capabilities of Soils by texture. (Figure 5.9. As seen in Foth, 1990)

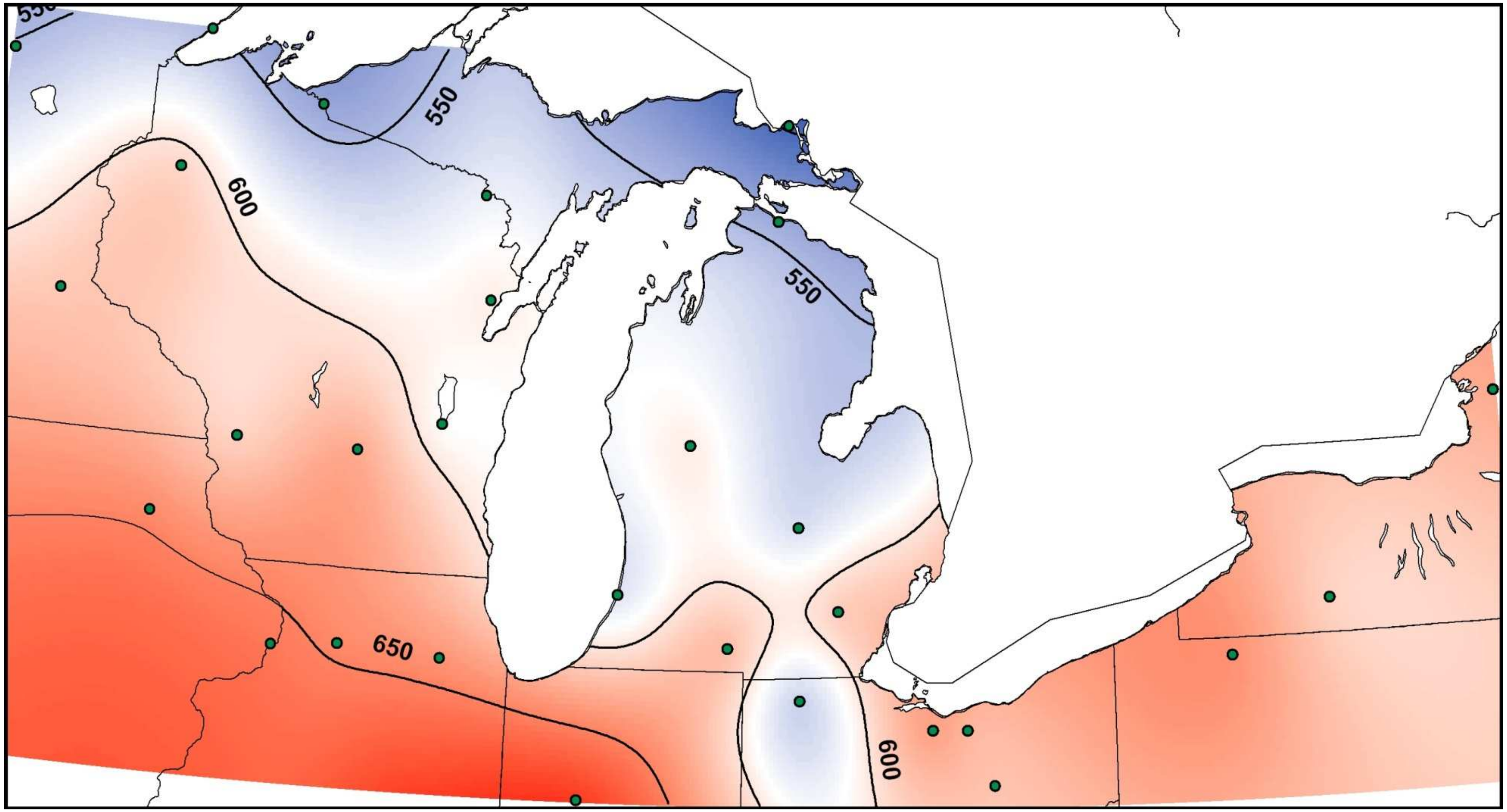

Figure 5: Average Annual Evapotranspiration (mm) for a grassland land cover on a loamy soil, 1979-2008.

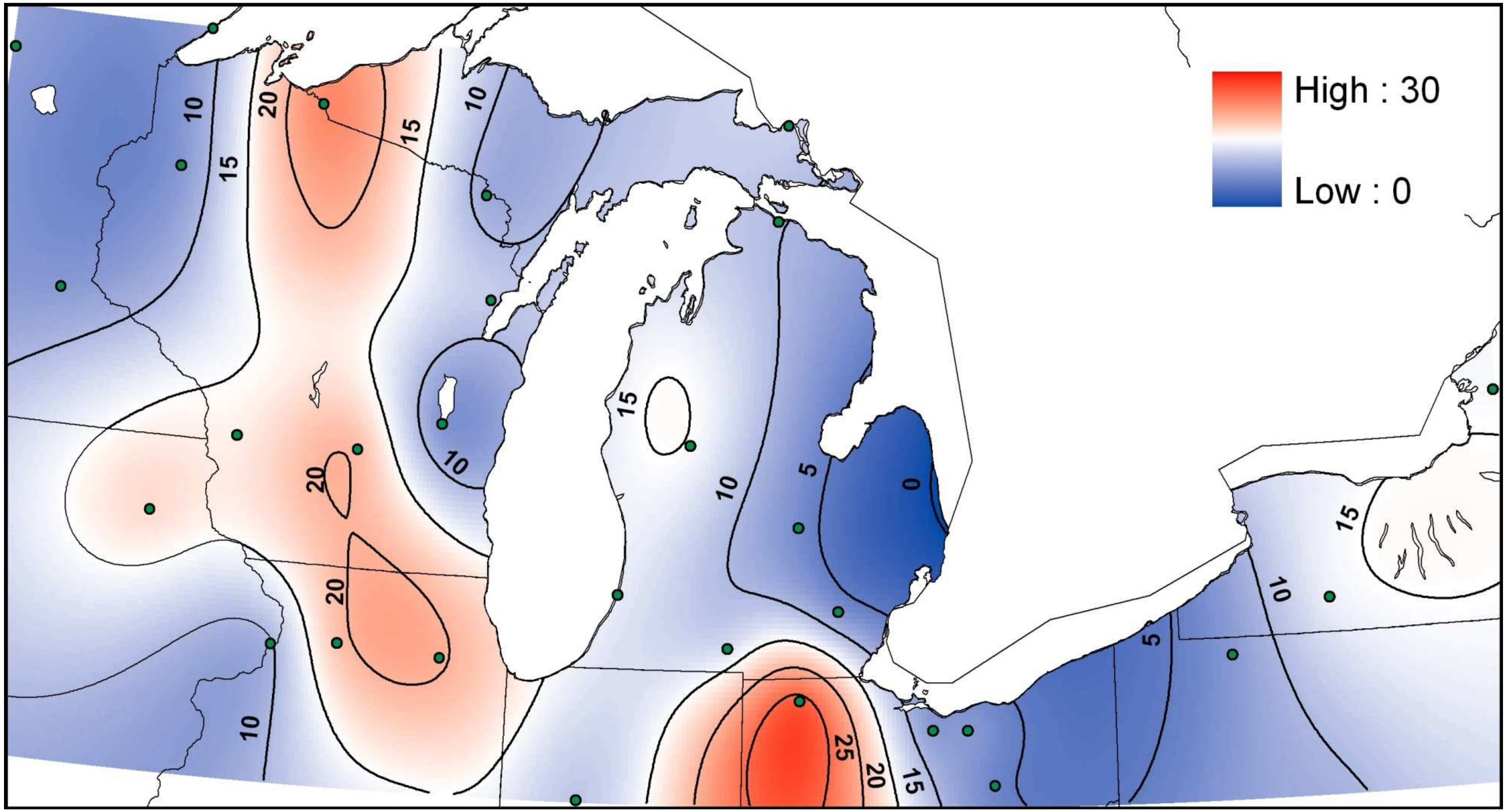

Figure 6: Average Annual Runoff (mm) for a grassland land cover on a loamy soil, 1979-2008.

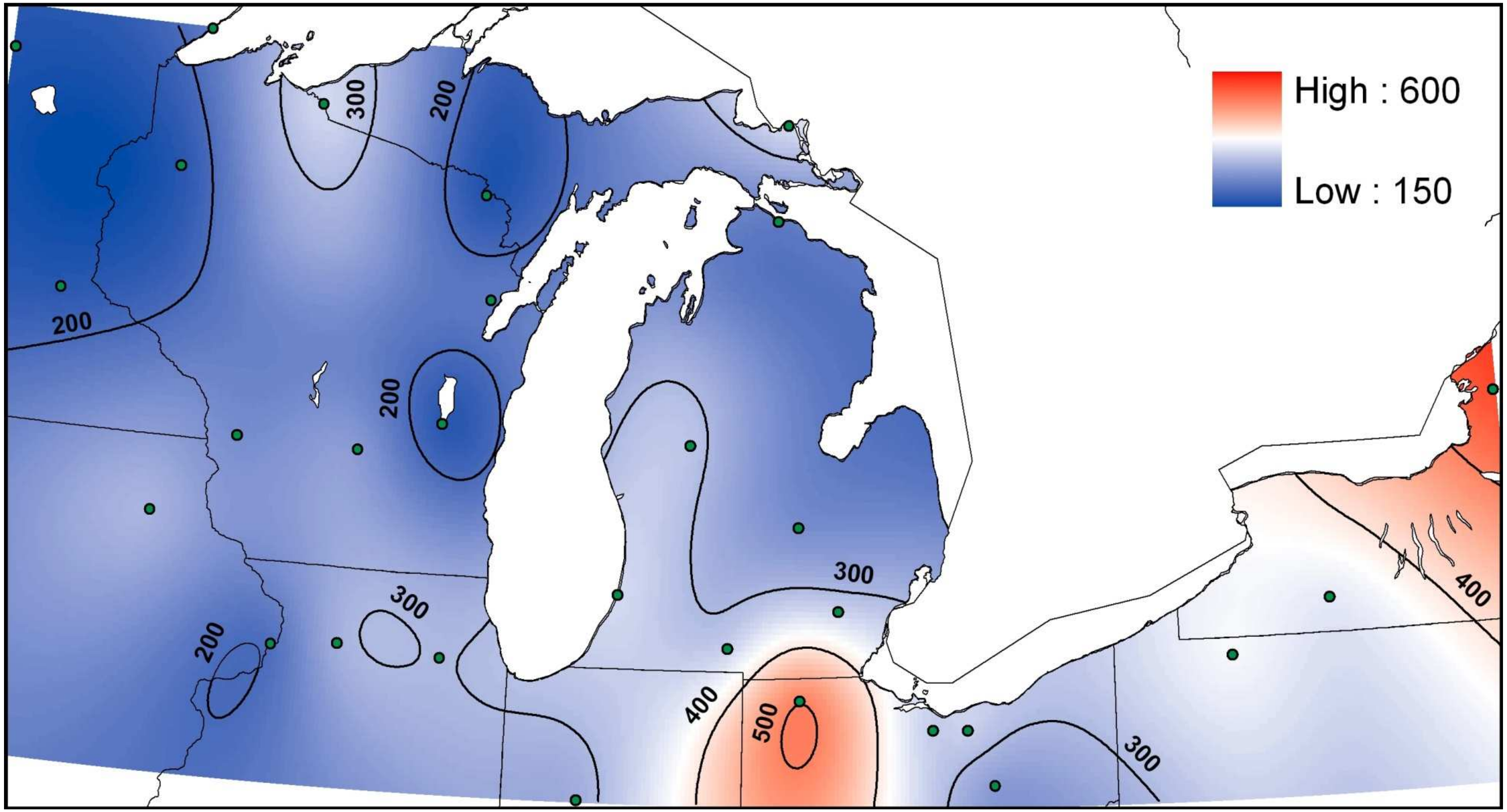

Figure 7: Average Annual Drainage (mm) for a grassland land cover on a loamy soil, 1979-2008.

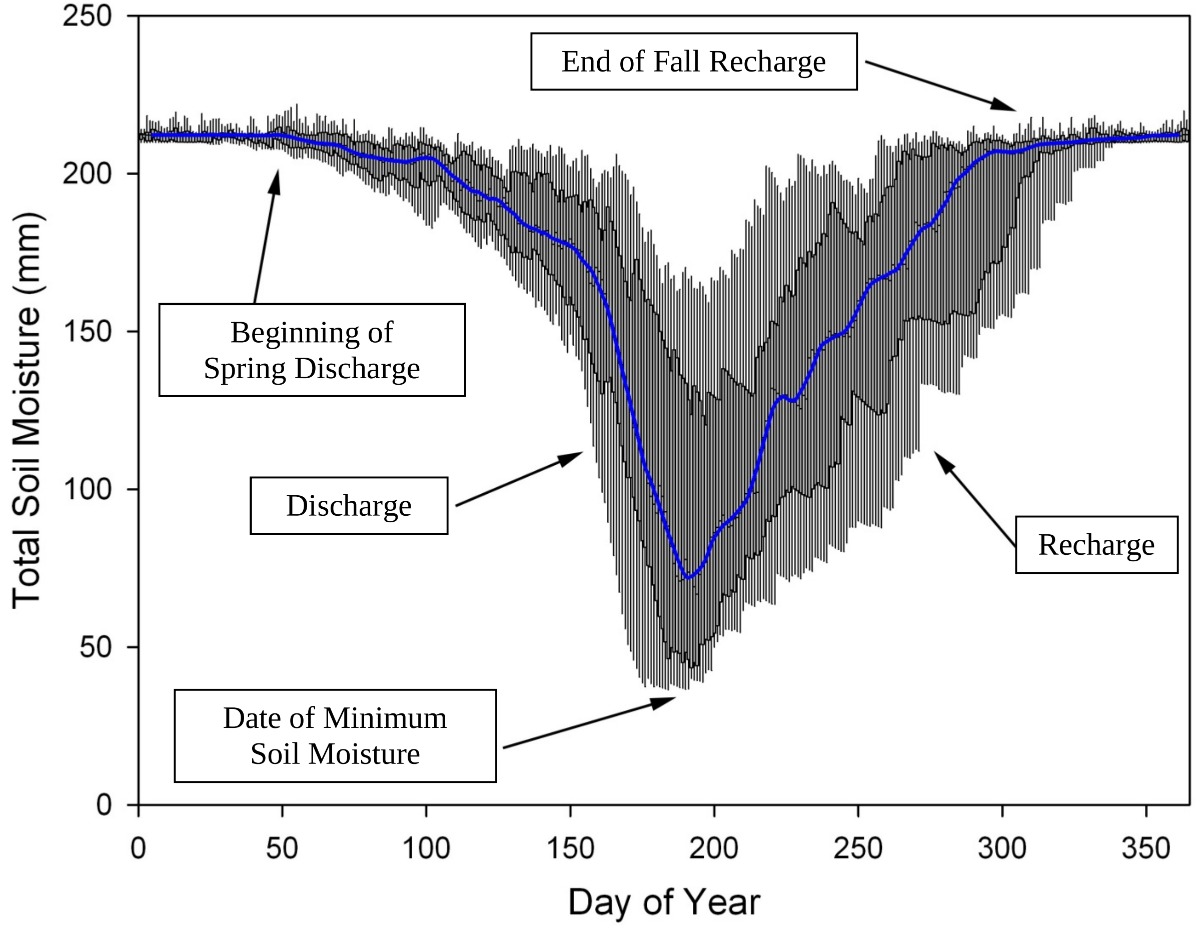

Figure 8: Example of an annual soil moisture curve, 1979-2008, South Haven, MI. Corn land cover and Loam soil type.

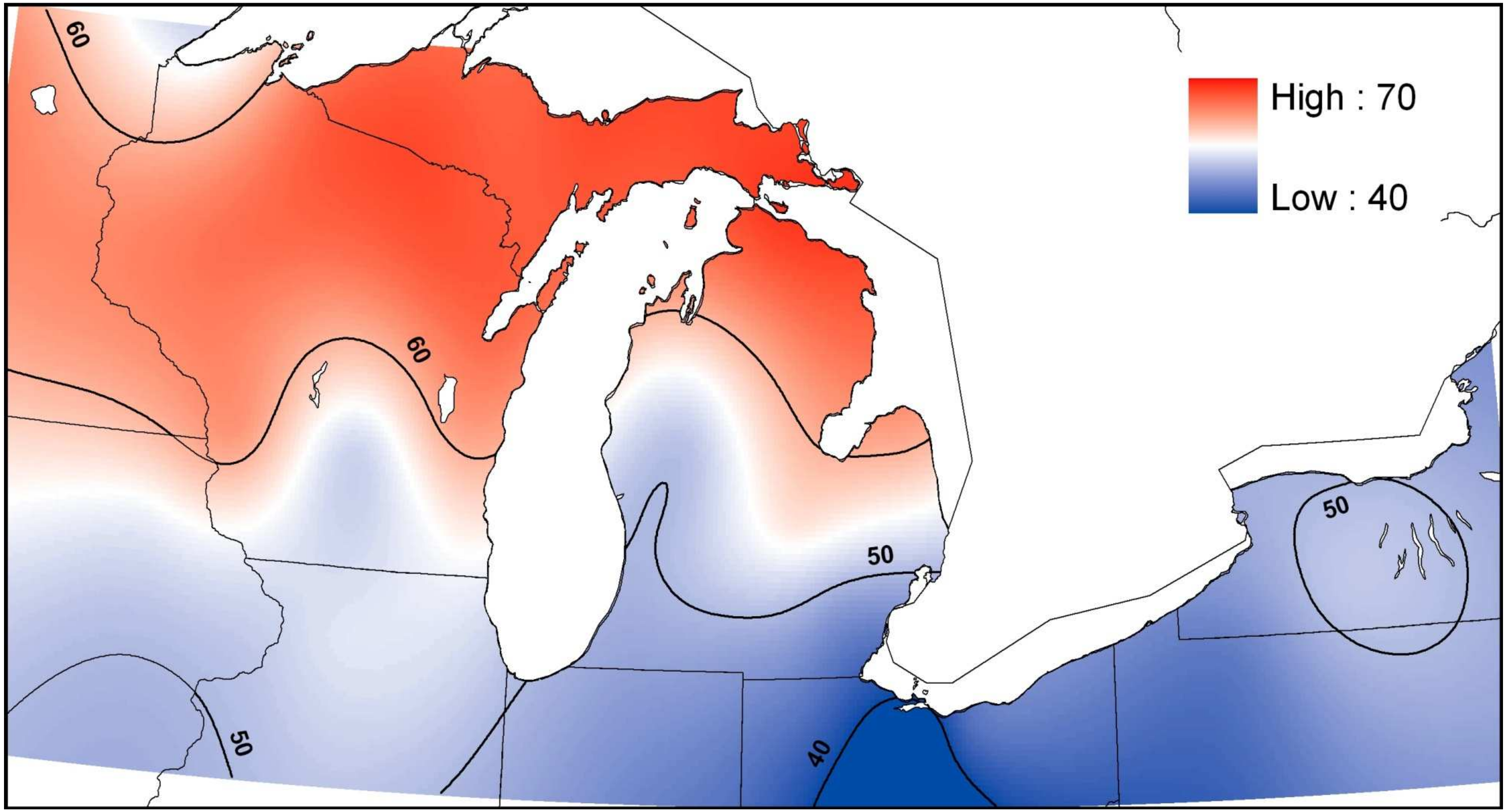

Figure 9: Average Date of Soil Moisture Discharge averaged across soil textures, Pasture Land Cover, 1979-2008.

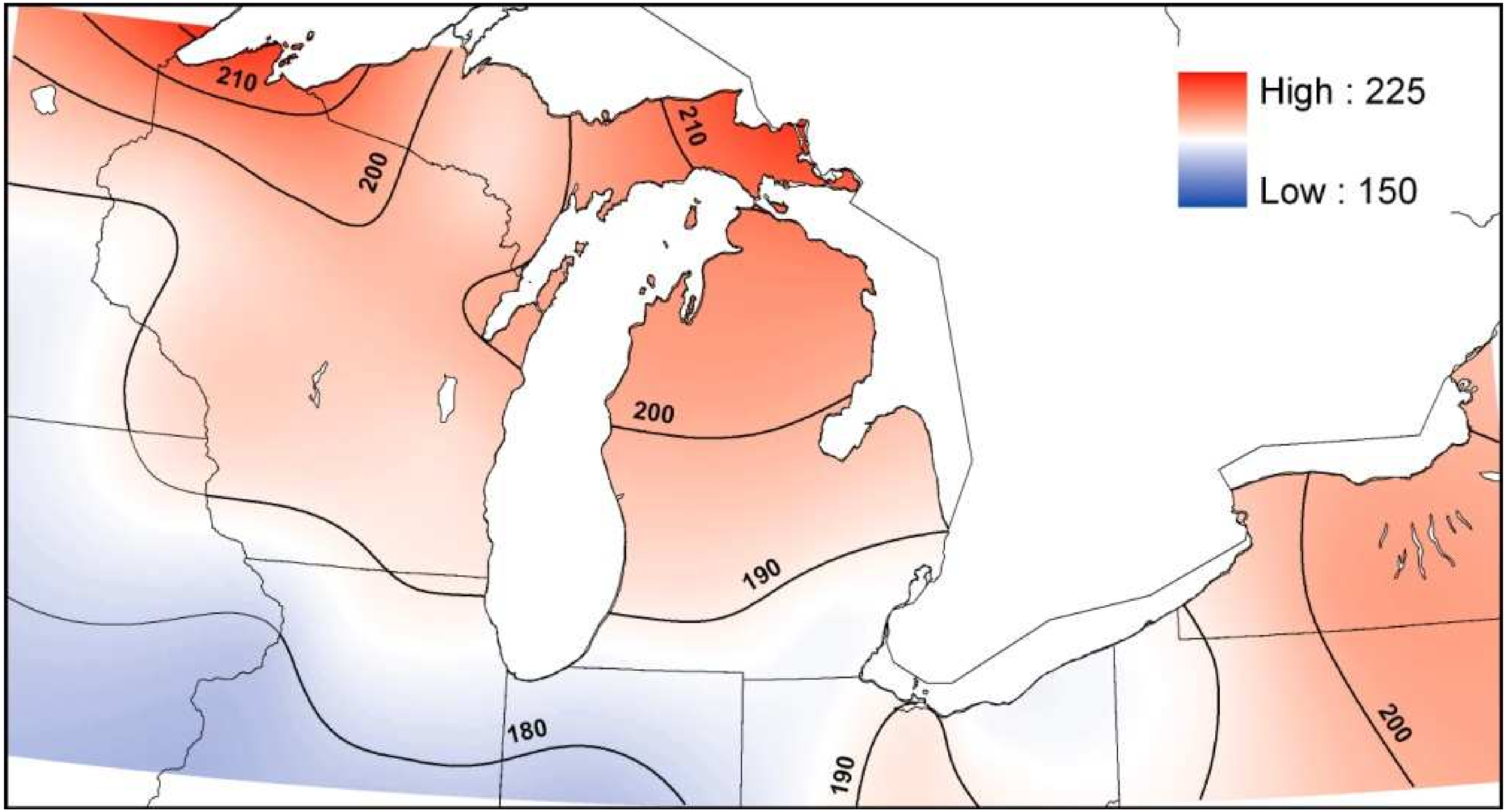

Figure 10a: Average Date of Minimum Soil Moisture, averaged across soil textures, Corn land cover. 1979-2008.

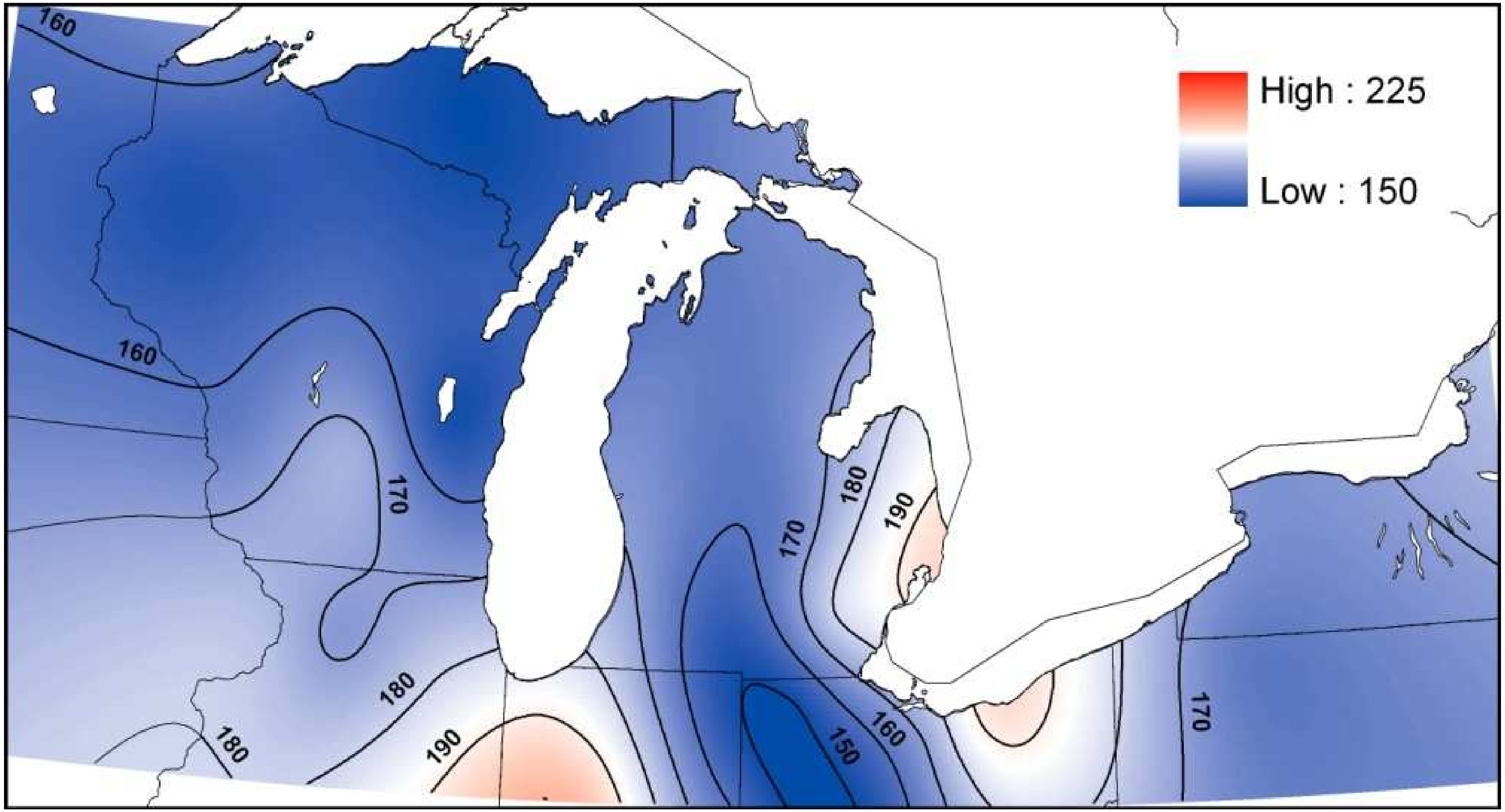

Figure 10b: Average Date of Minimum Soil Moisture, averaged across soil textures, Wheat land cover. 1979-2008.

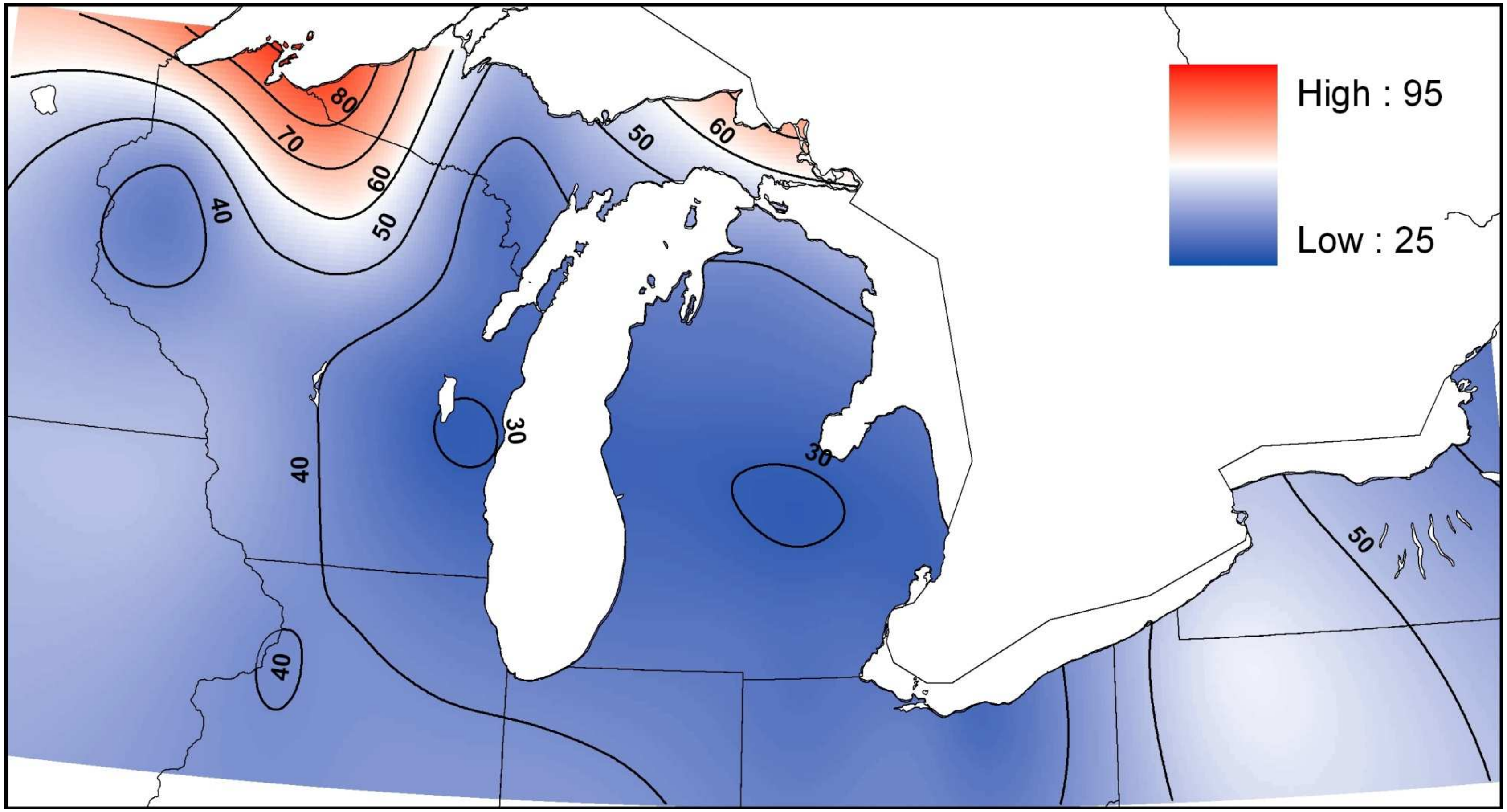

Figure 11: Average Minimum Soil Moisture amount, averaged across soil textures, Wheat land cover, 1979-2008.

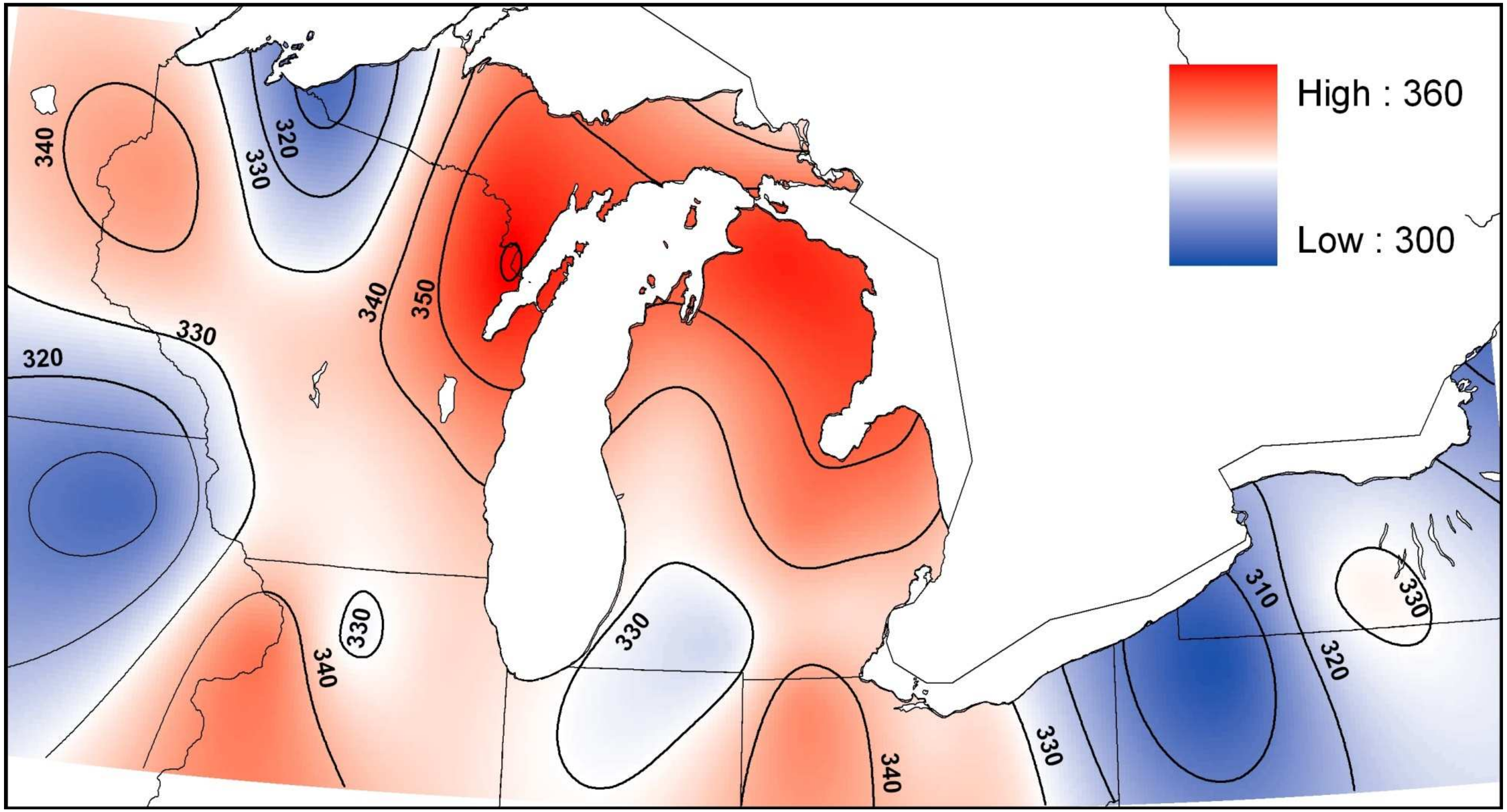

Figure 12: Average Date of Soil Moisture Recharge, averaged across soil textures, Pasture land cover, 1979-2008.

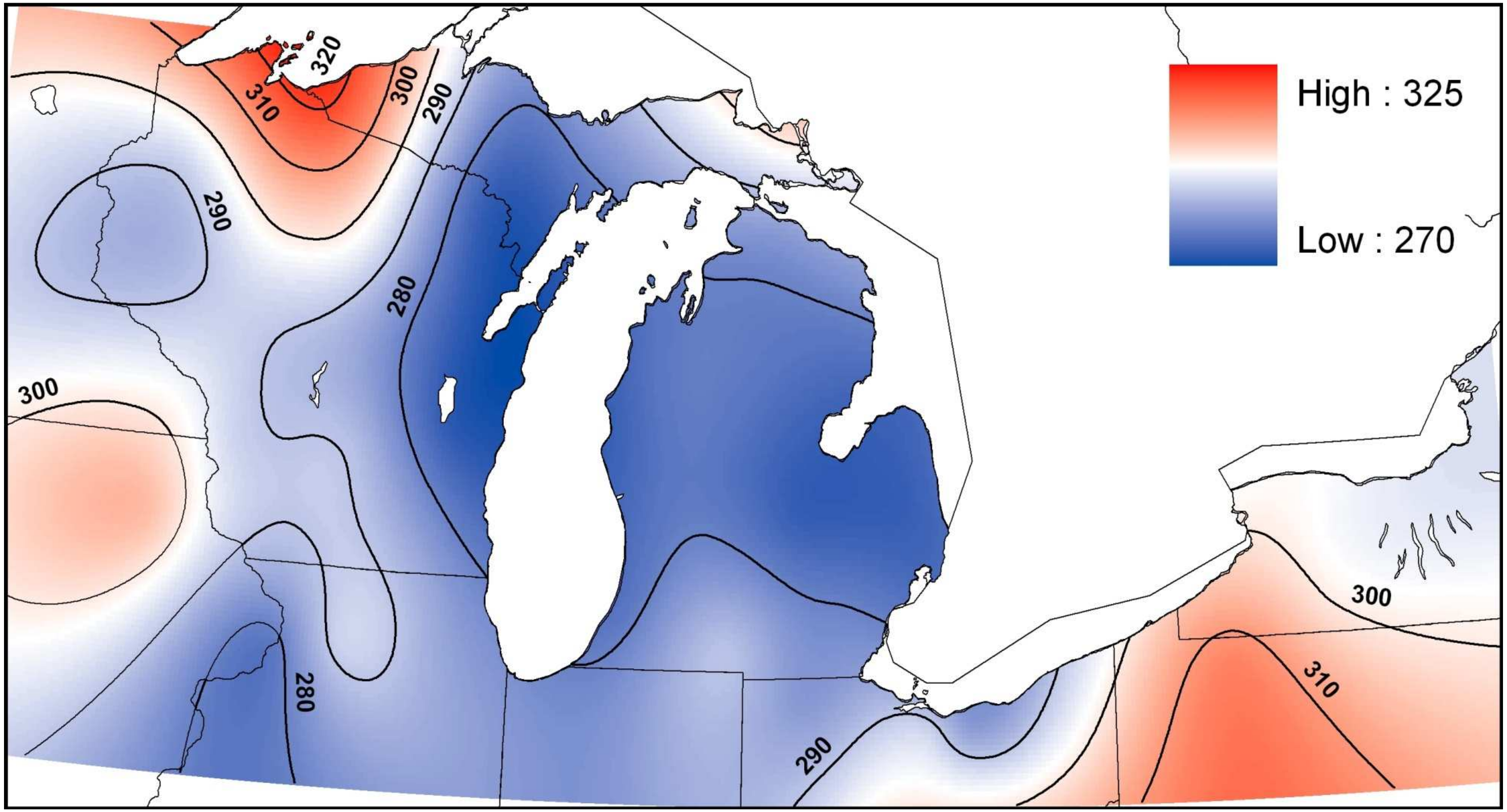

Figure 13: Average Annual Soil Moisture Days, averaged across soils, Pasture land cover, 1979-2008.

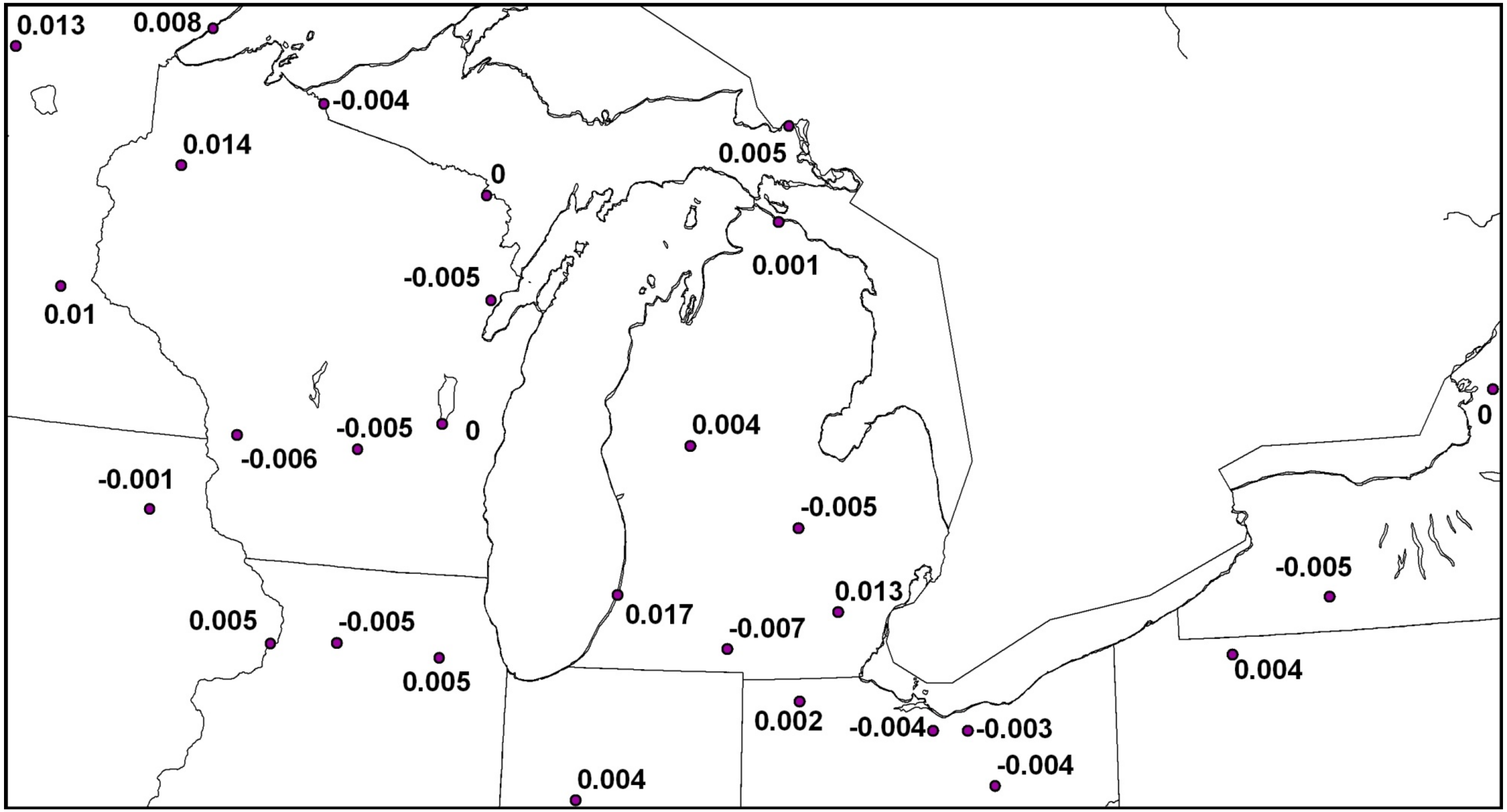

Figure 14: Trends in Temperature (C/year) across the study area, 1900-2008.

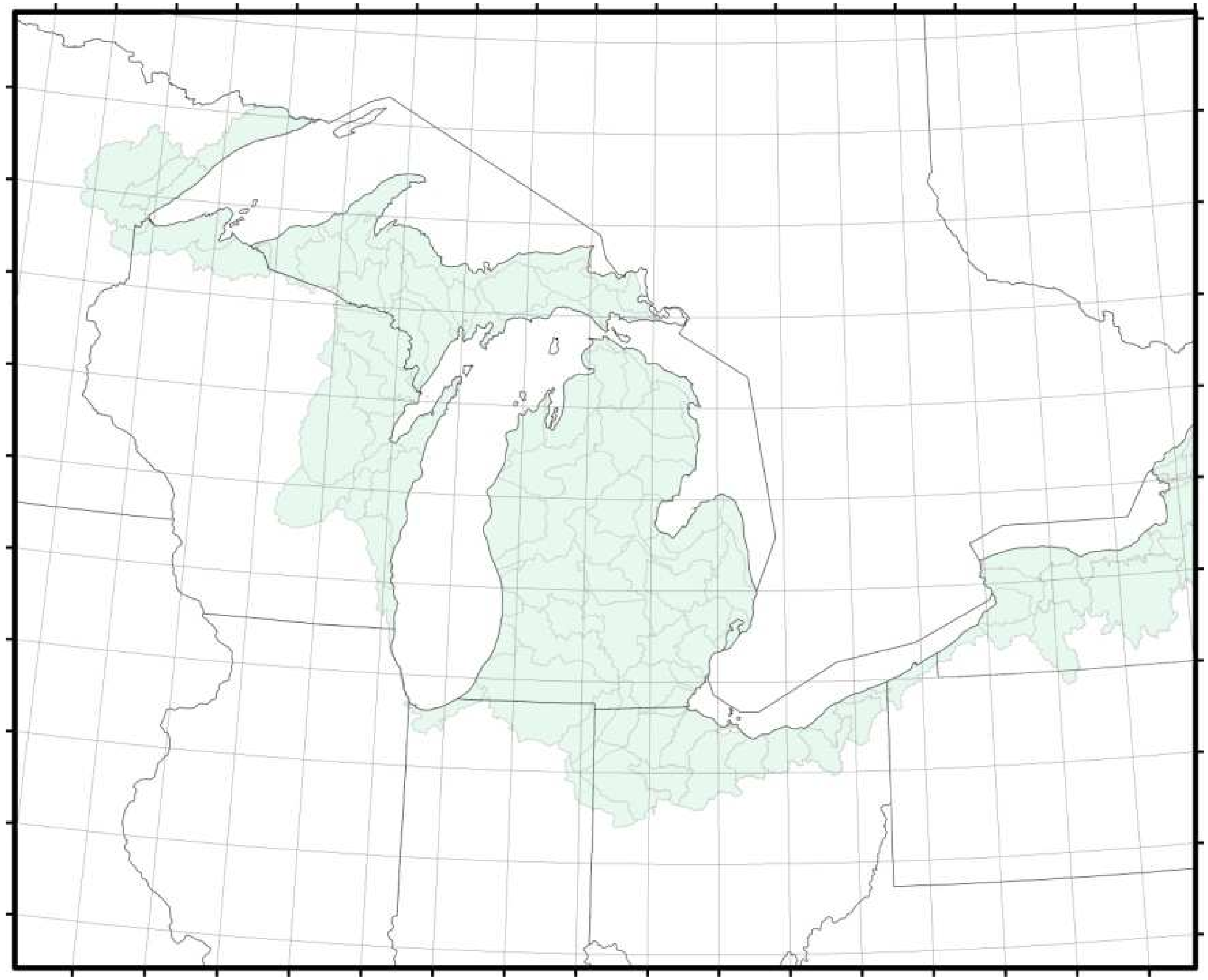

Figure 15: Great Lakes Drainage Basin

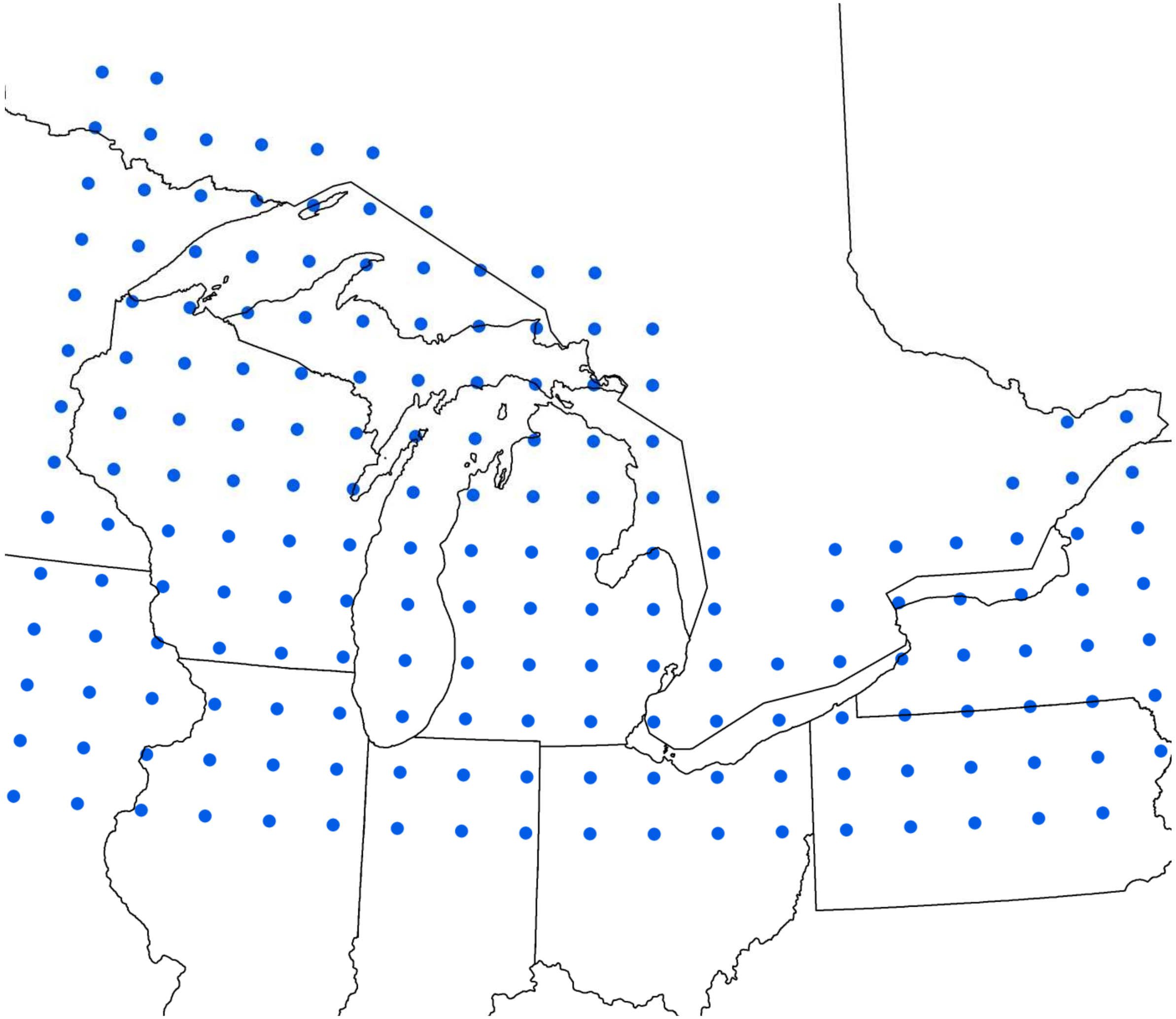

Figure 16: Center of Grids from Midwestern Regional Climate Center.

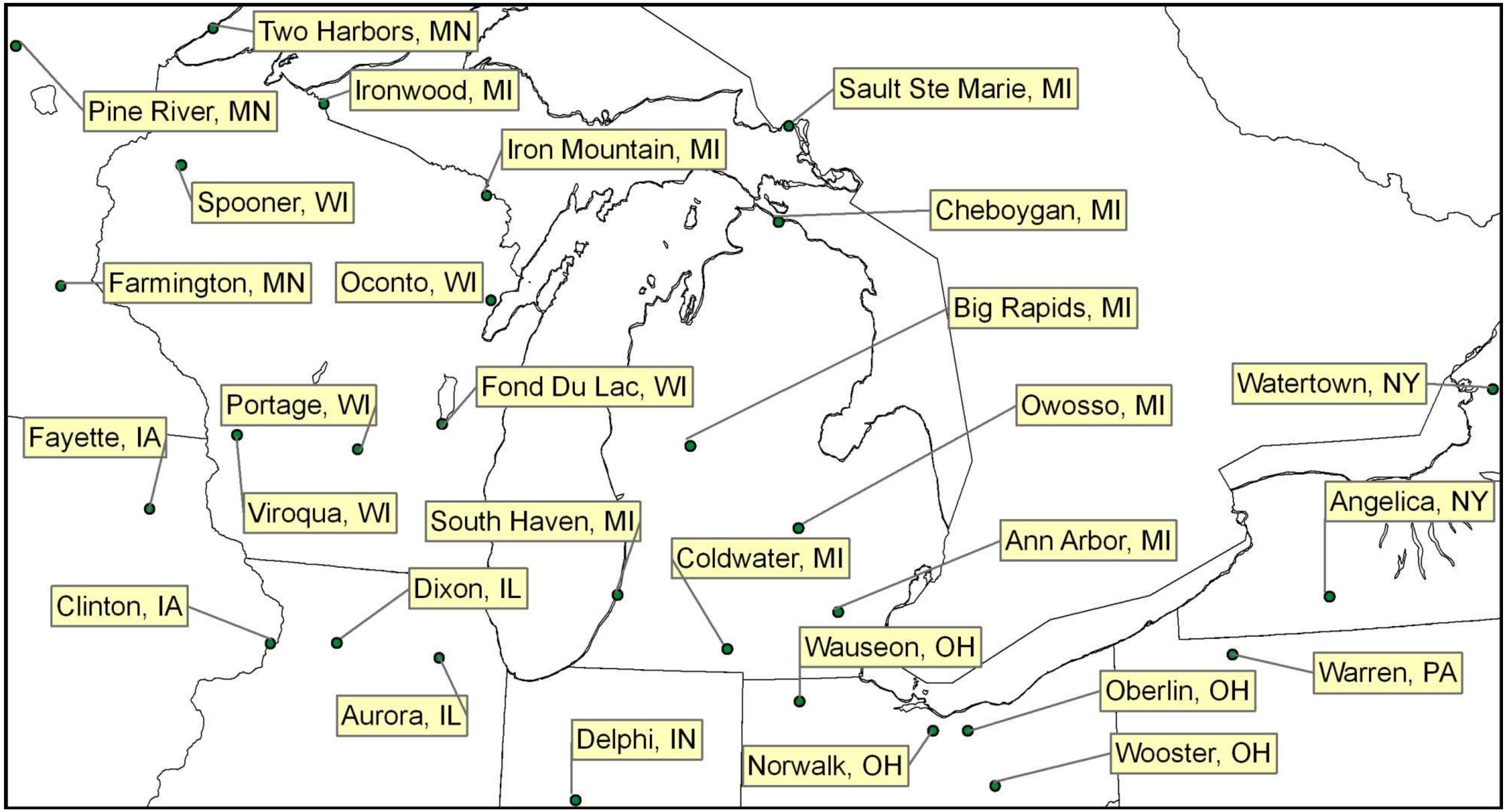

Figure 17: Map of Historical Climate Network Observation Sites used for this study.

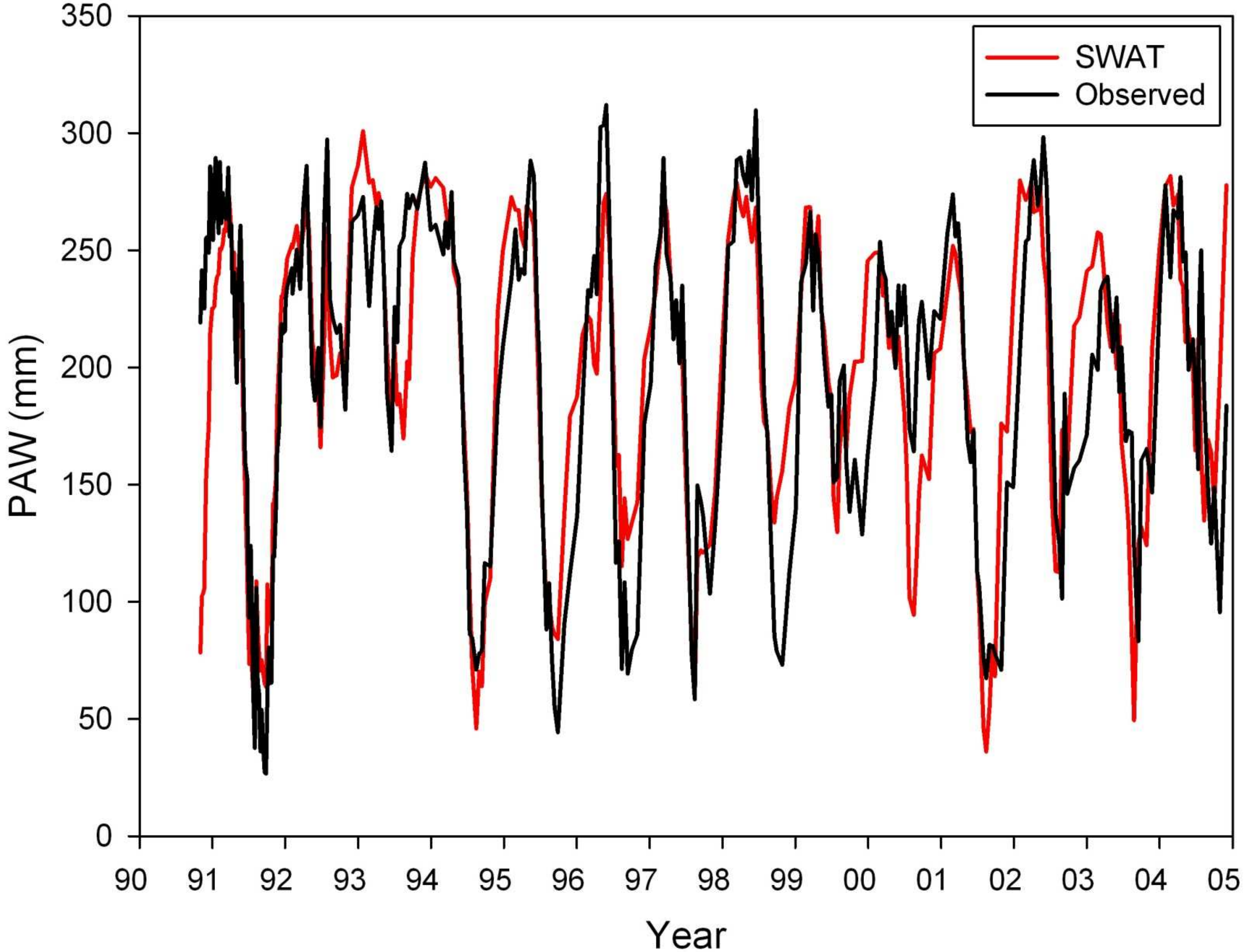

Figure 18a: Comparison of SWAT plant available soil moisture to Observed plant available soil moisture. Bondville, IL.

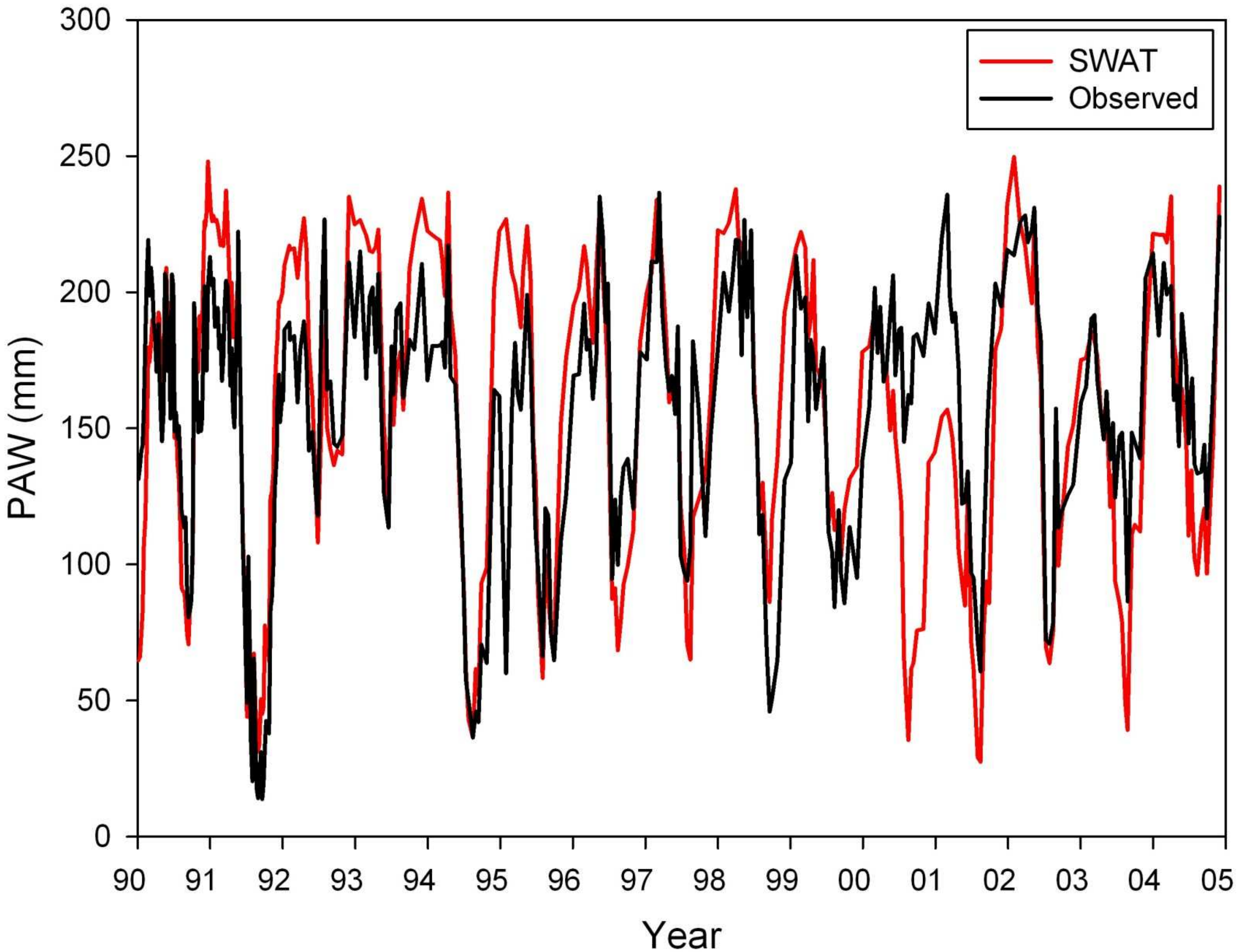

Figure 31b: Comparison of SWAT plant available soil moisture to Observed plant available soil moisture. Champaign, IL.

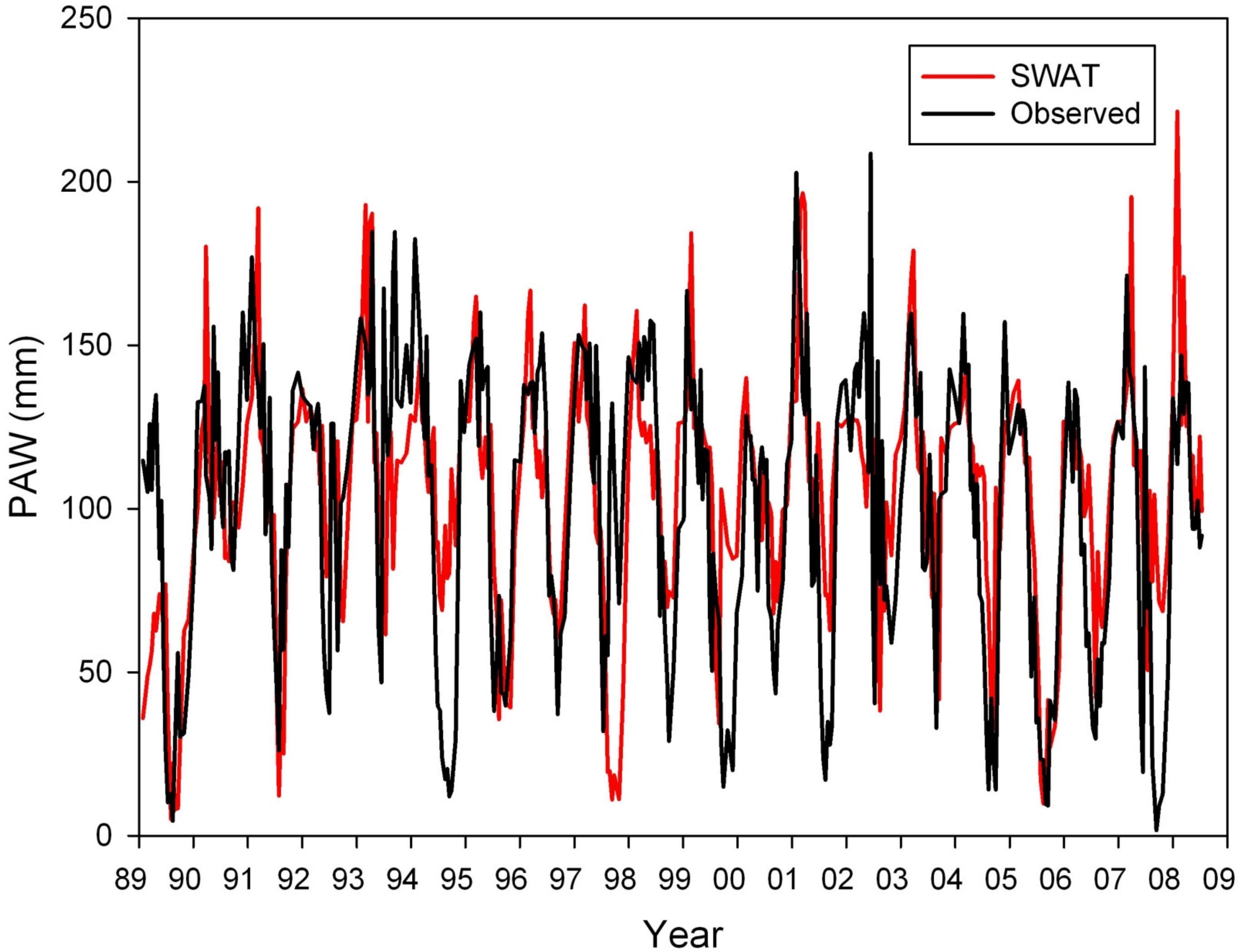

Figure 31c: Comparison of SWAT plant available soil moisture to Observed plant available soil moisture. Topeka, IL.

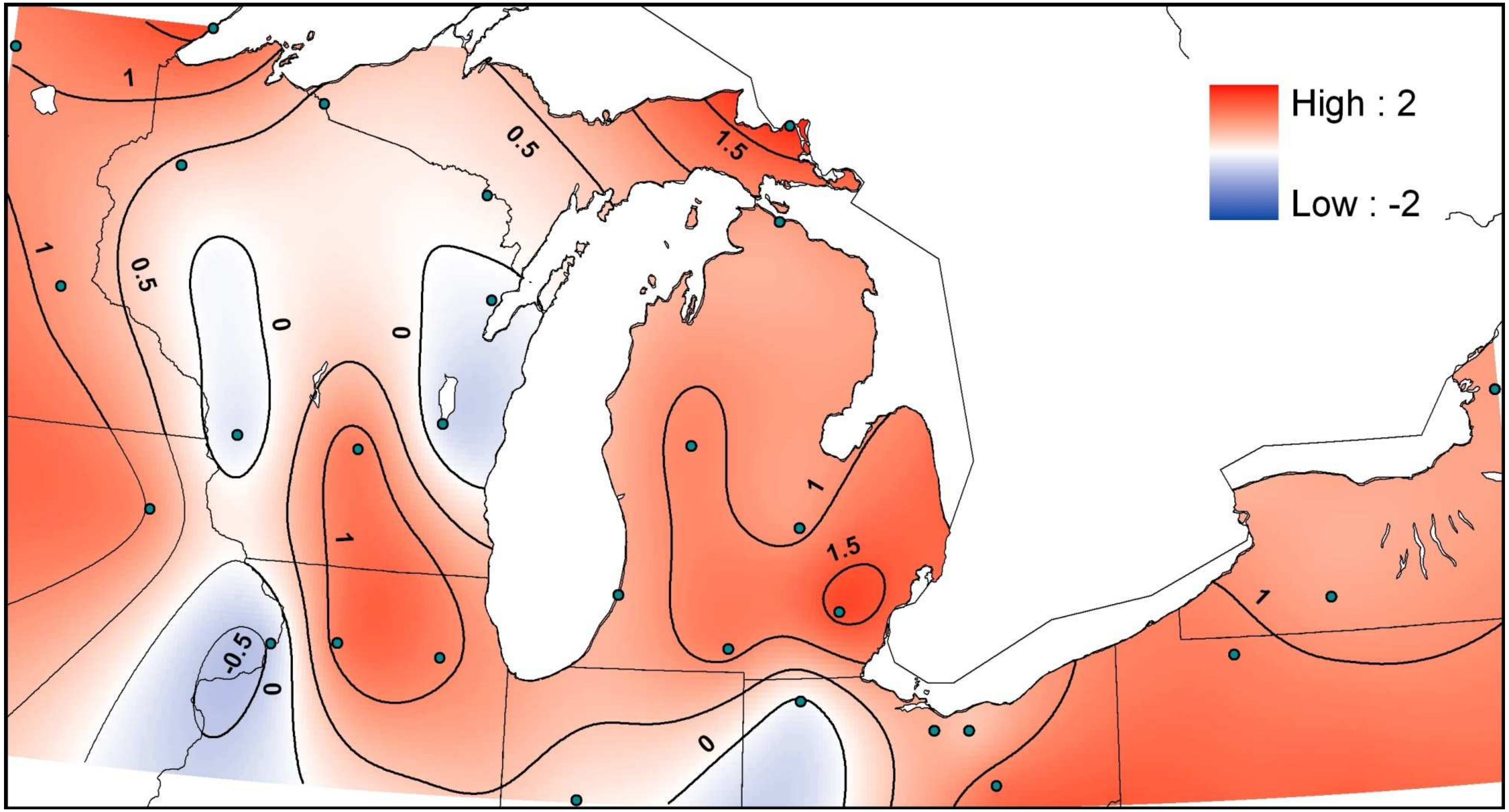

Figure 19: Rate of Change: Precipitation (mm/year) 1900-2008. Contours are at 0.5 mm/year intervals.

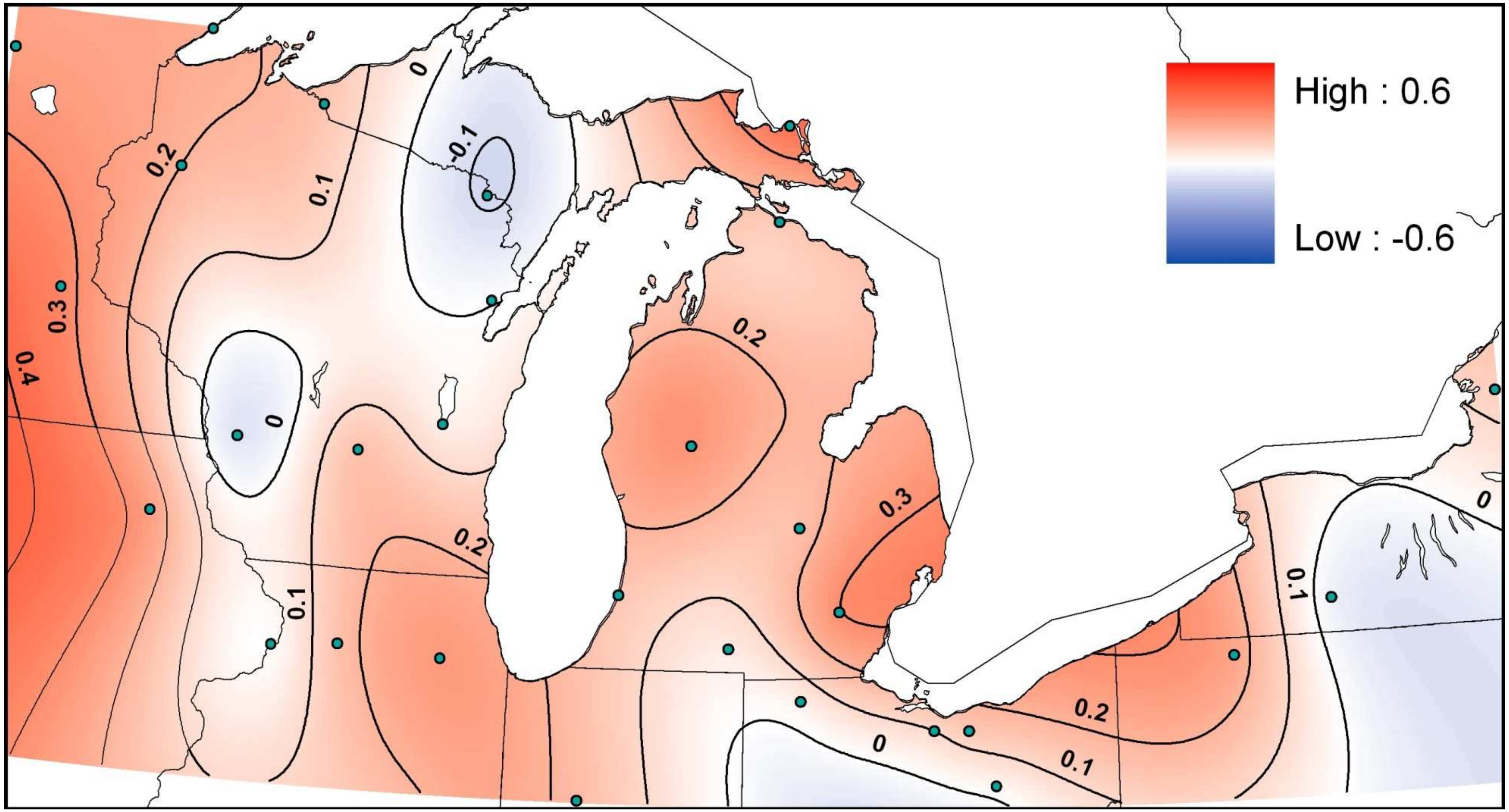

Figure 20: Rate of change of Evapotranspiration. Average of all soils, Corn land cover (mm/year), 1900-2008. Contours are 0.1 mm/year.

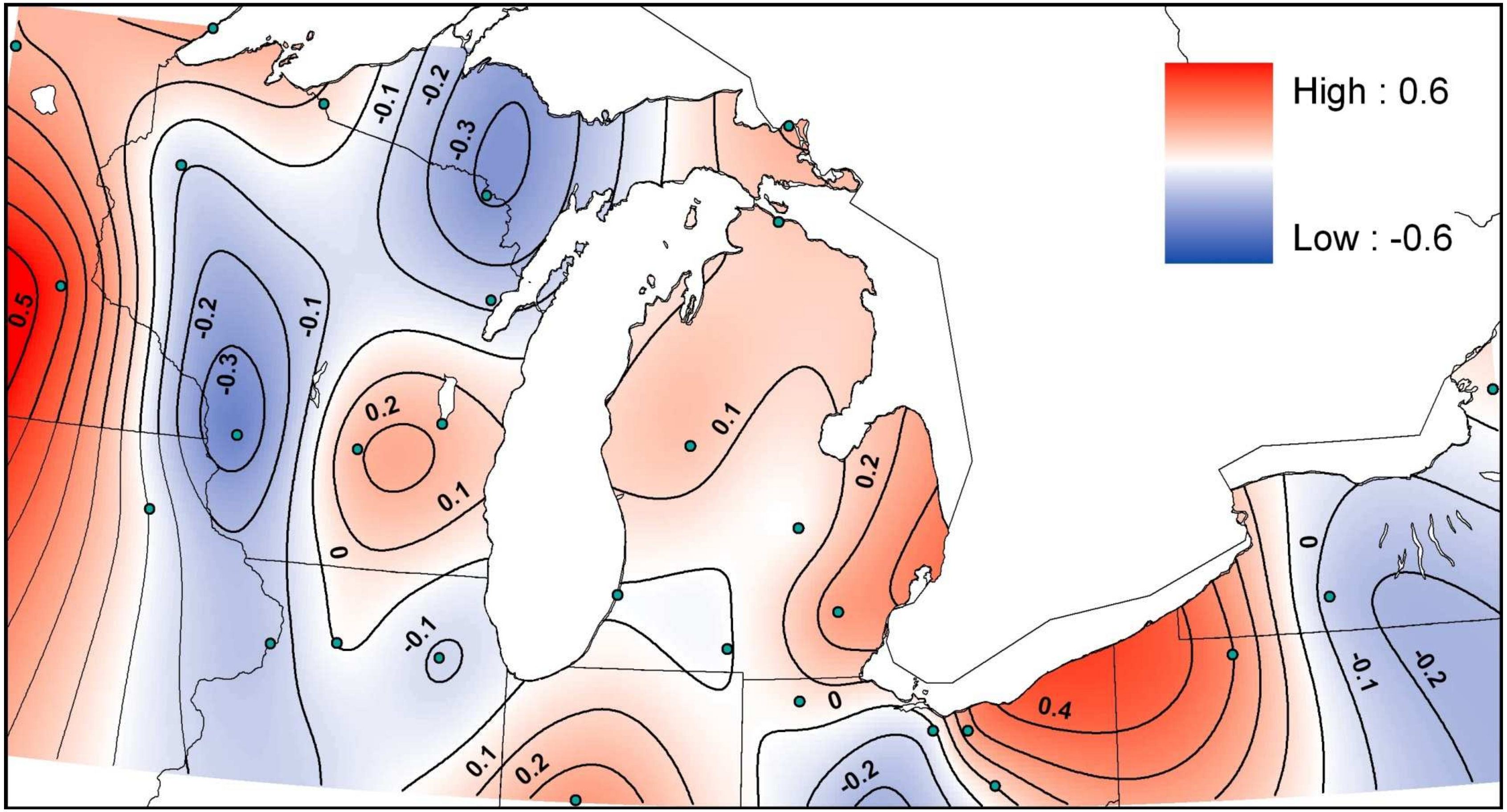

Figure 21: Rate of change of Evapotranspiration. Average of all soils, Forest land cover (mm/year). Contours are 0.1 mm/year.

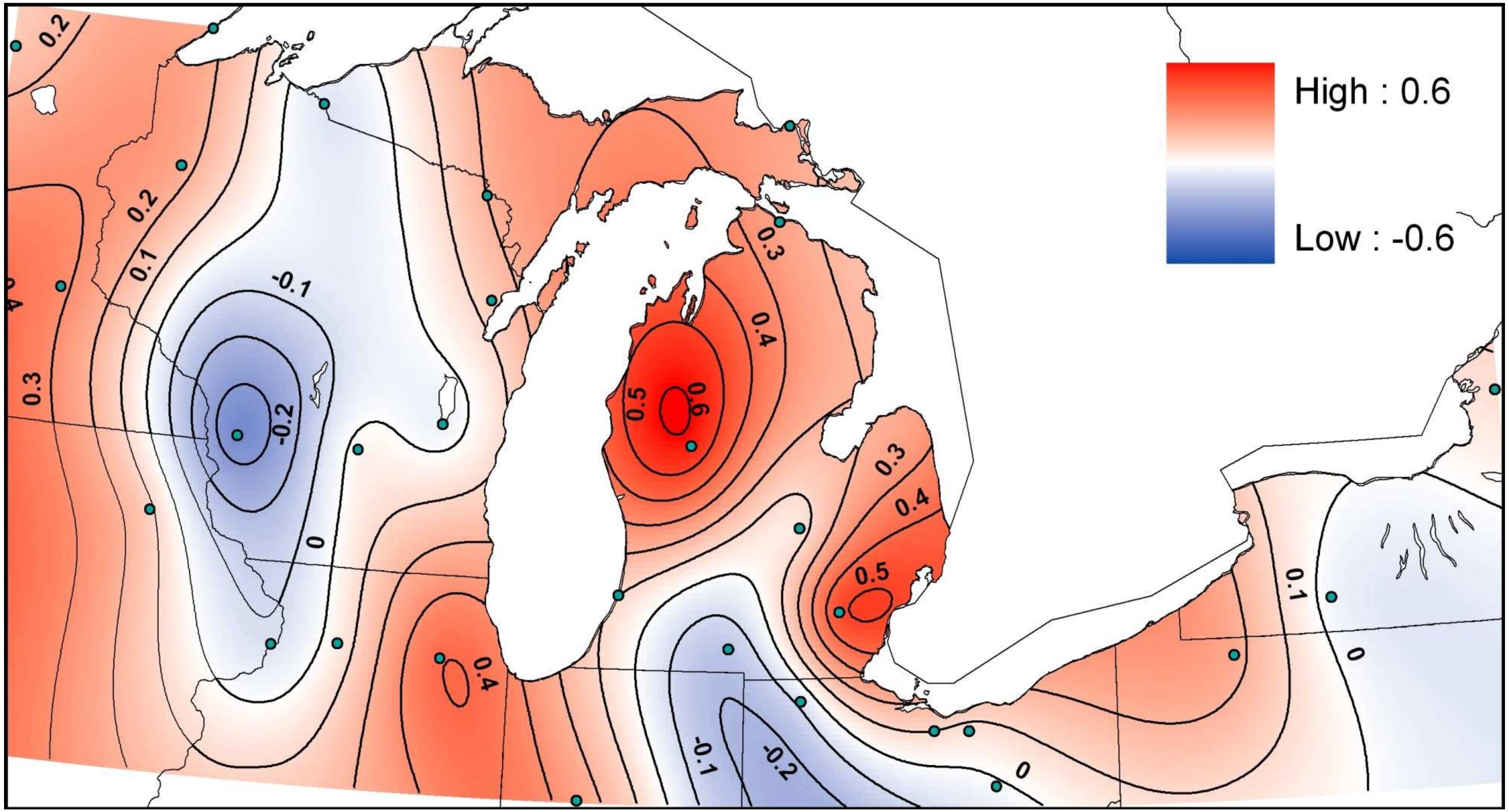

Figure 22: Rate of change of Evapotranspiration. Average of all soils, Pasture land cover (mm/year). Contours are 0.1 mm/year.

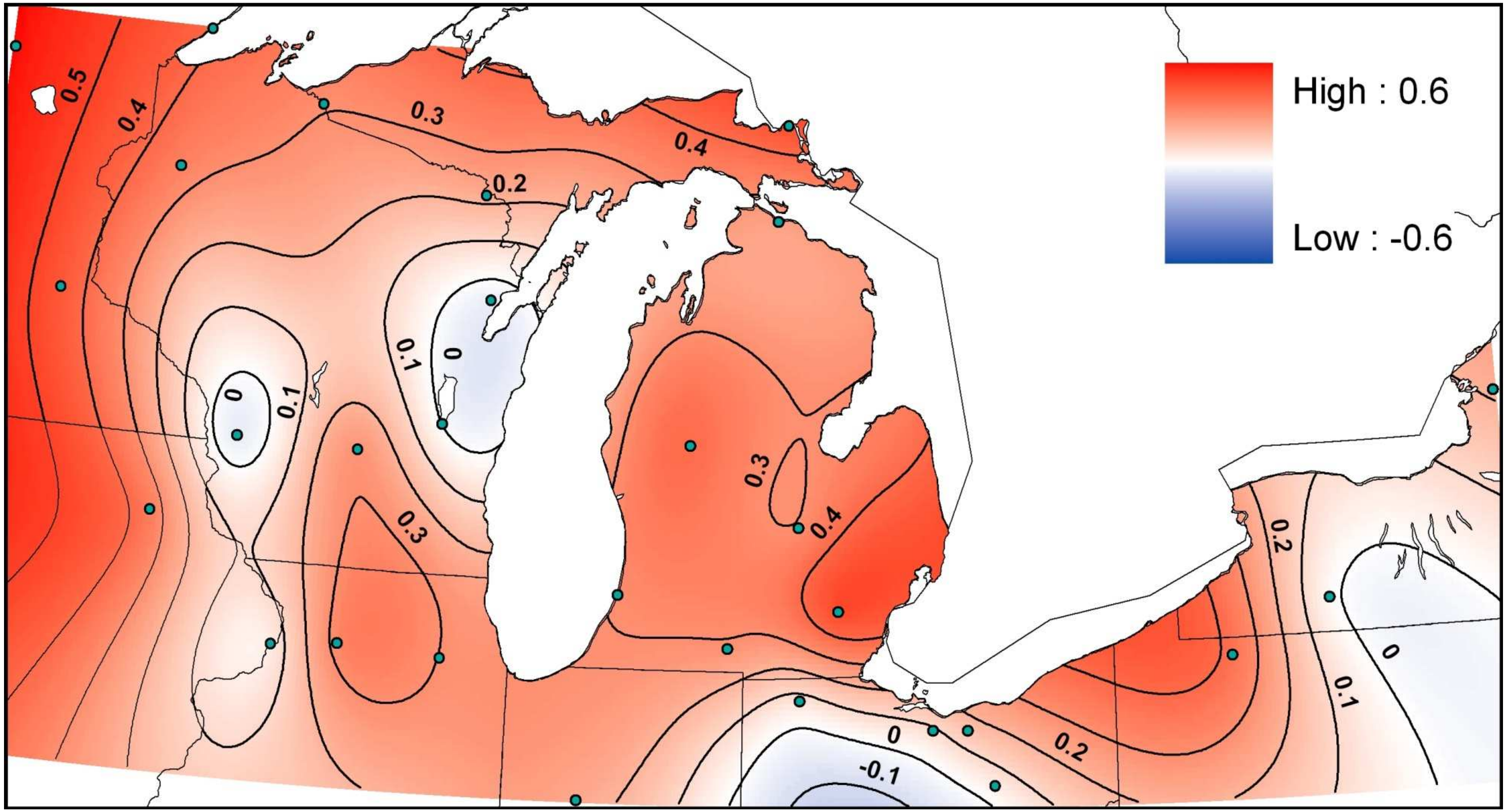

Figure 23: Rate of change of Evapotranspiration. Average of all soils, Urban land cover (mm/year). Contours are 0.1 mm/year.

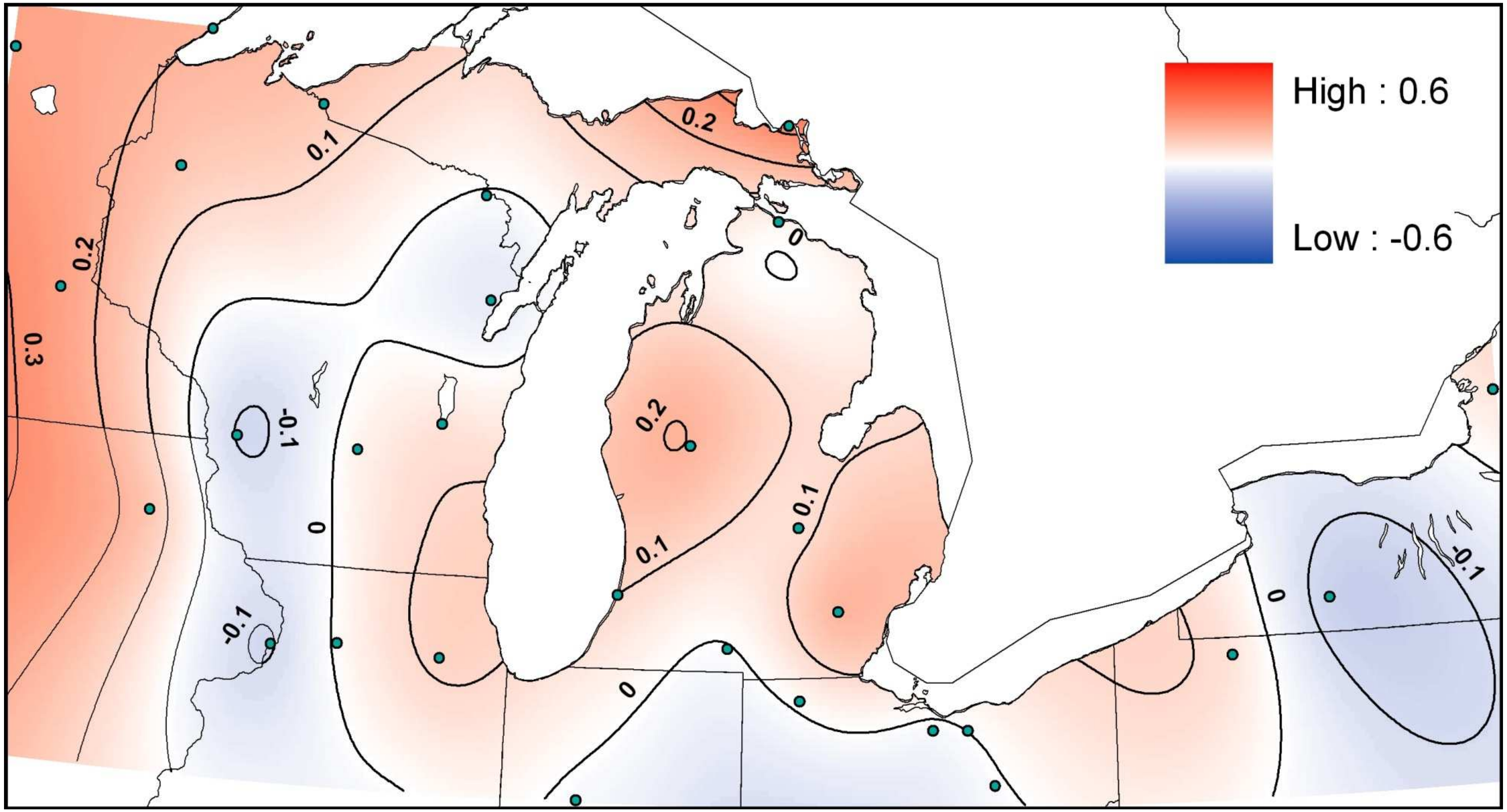

Figure 24: Rate of change of Evapotranspiration. Average of all soils, Wheat land cover (mm/year). Contours are 0.1 mm/year.

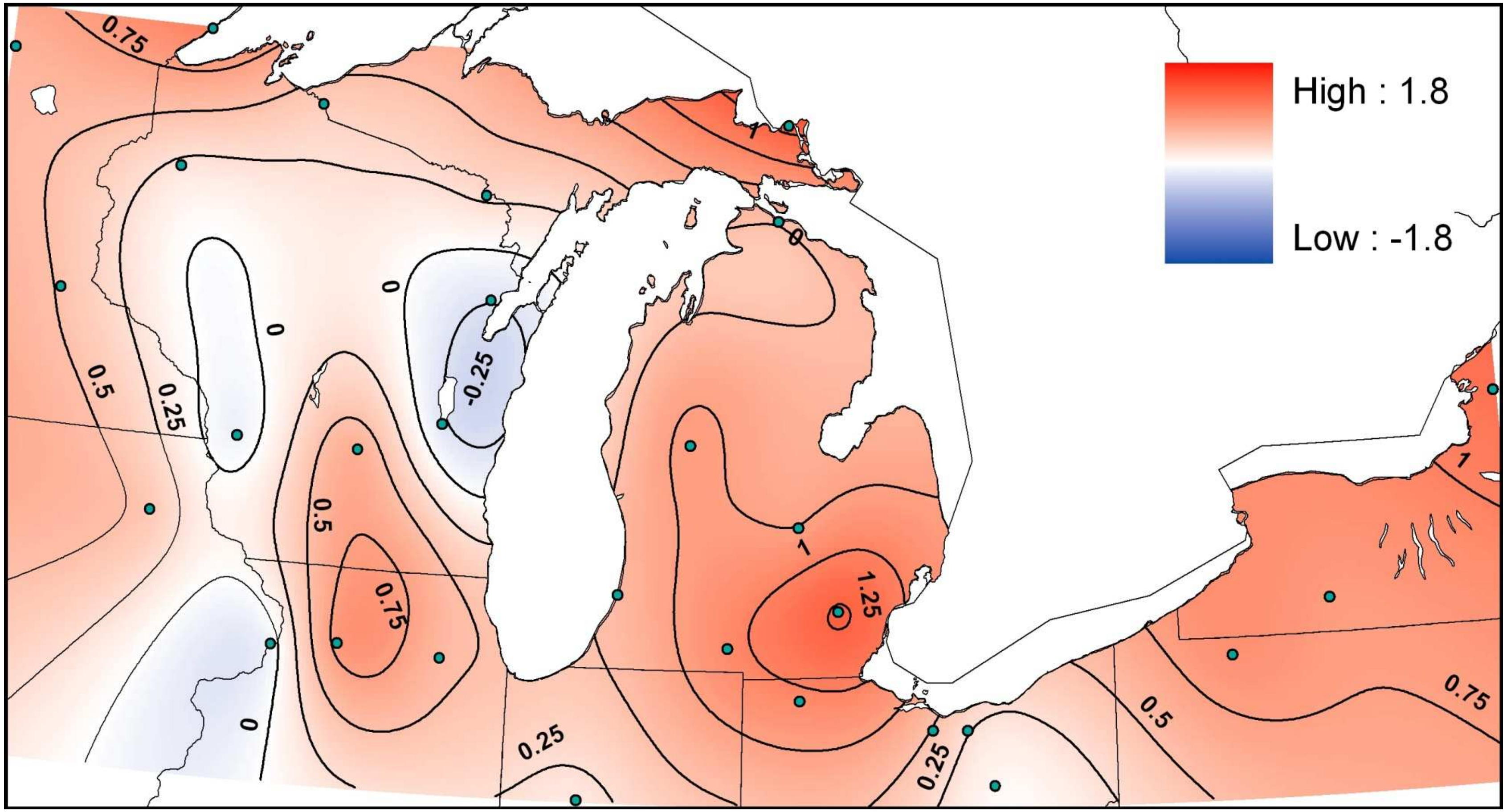

Figure 25: Rate of change of Percolation. Average of all soils, Corn land cover (mm/year). Contours are 0.25 mm/year.

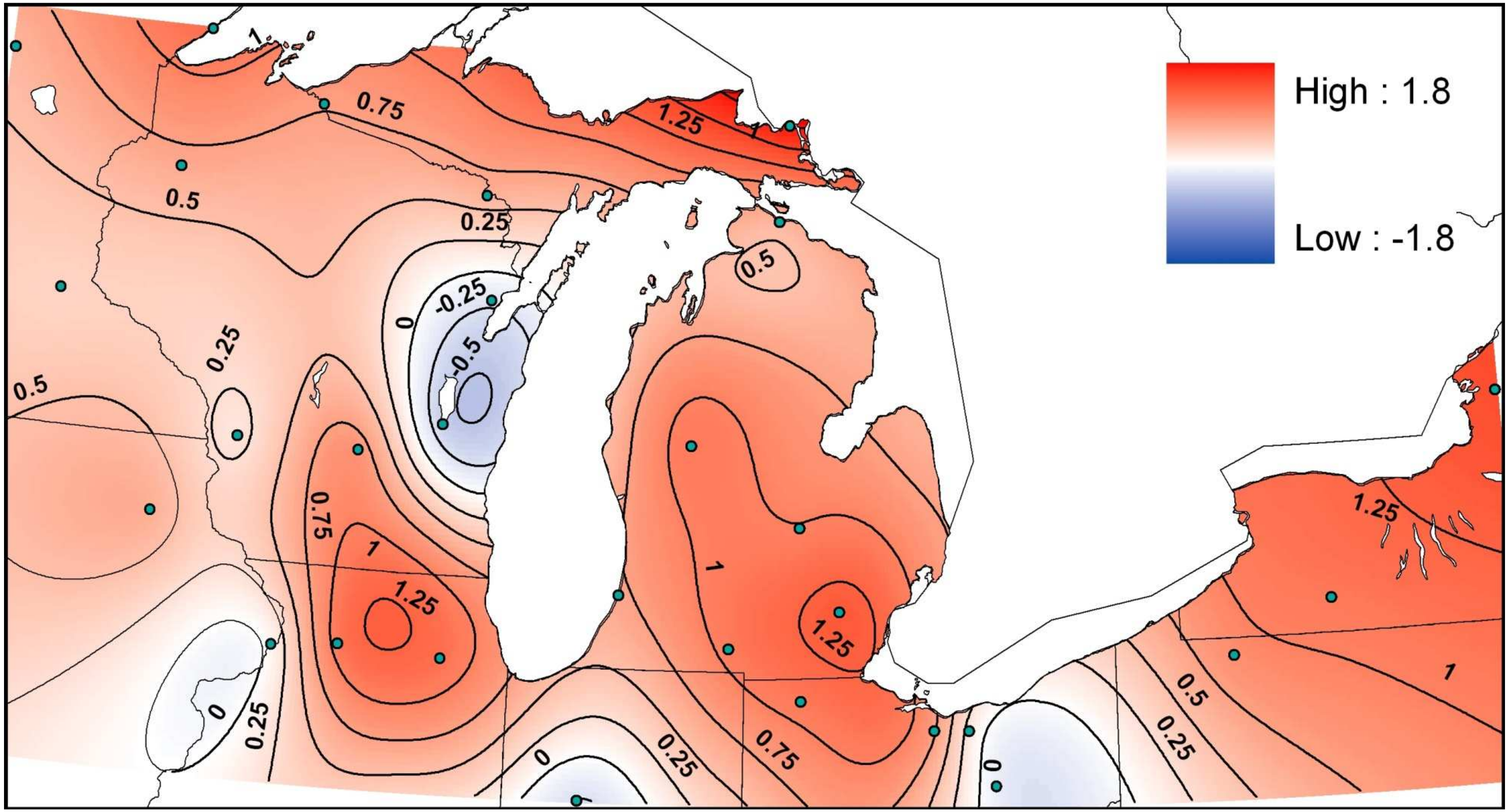

Figure 26: Rate of change of Percolation. Average of all soils, Forest land cover (mm/year). Contours are 0.25 mm/year.

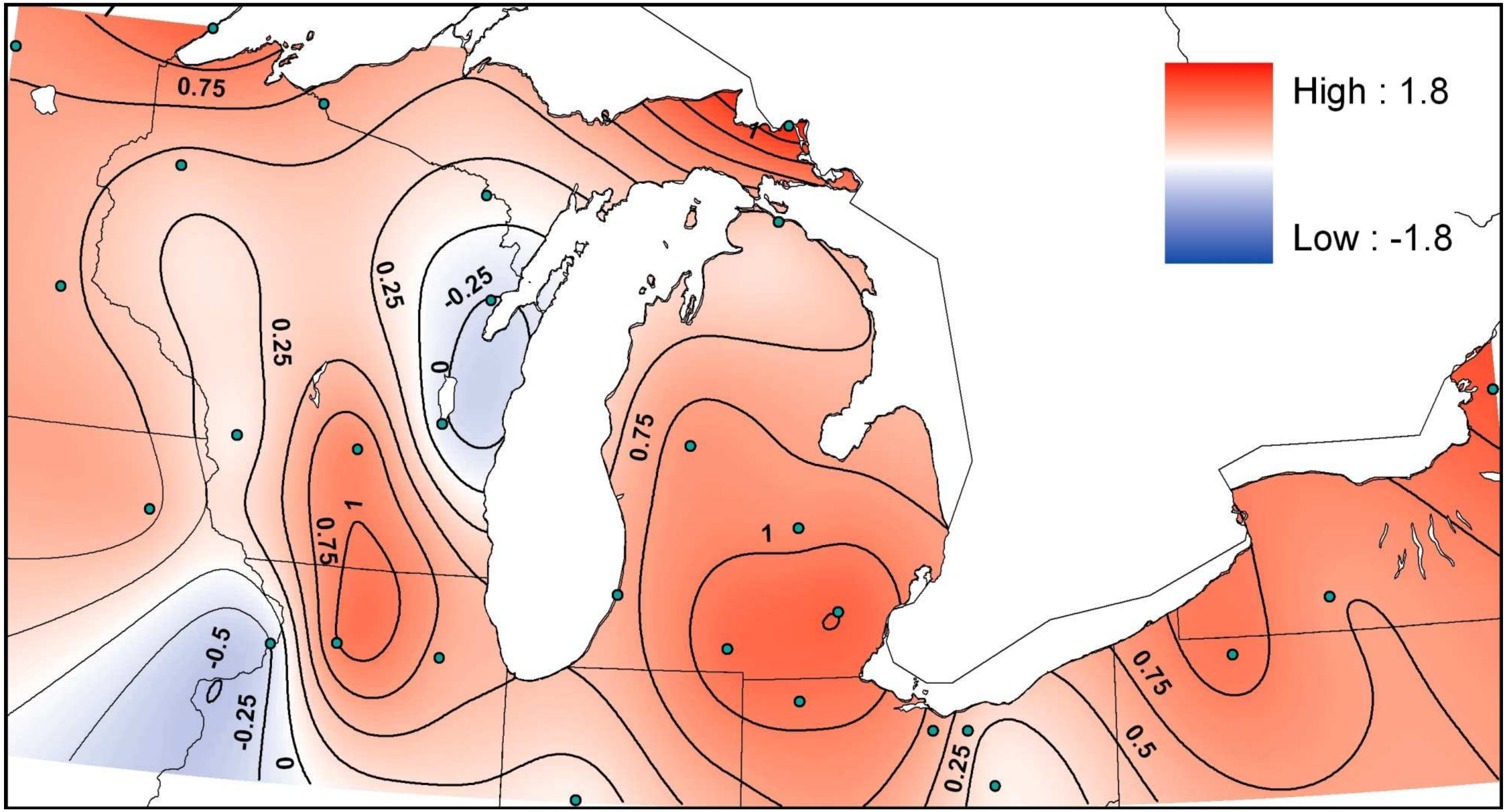

Figure 27: Rate of change of Percolation. Average of all soils, Pasture land cover (mm/year). Contours are 0.25 mm/year.

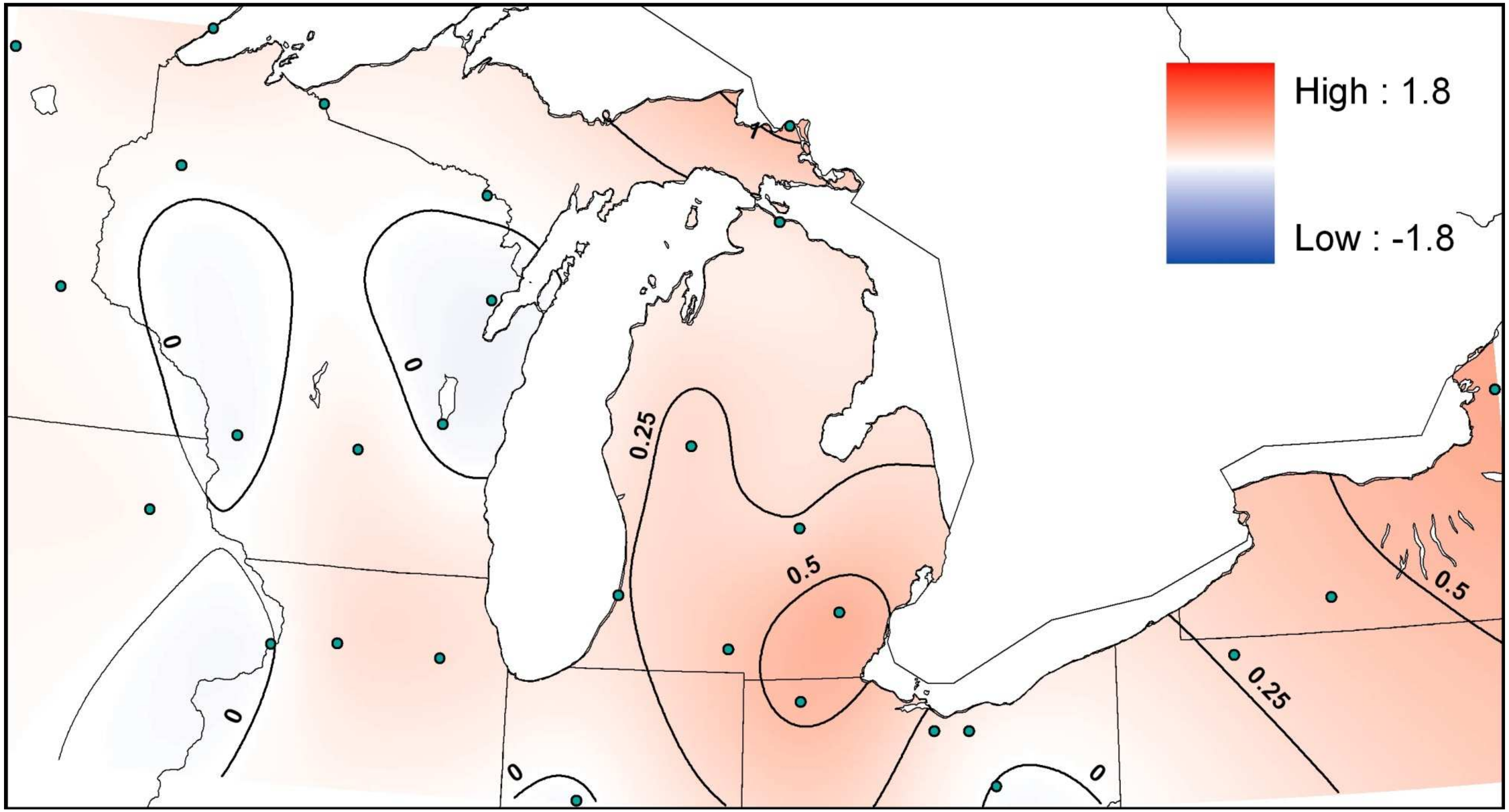

Figure 28: Rate of change of Percolation. Average of all soils, Urban land cover (mm/year). Contours are 0.25 mm/year.

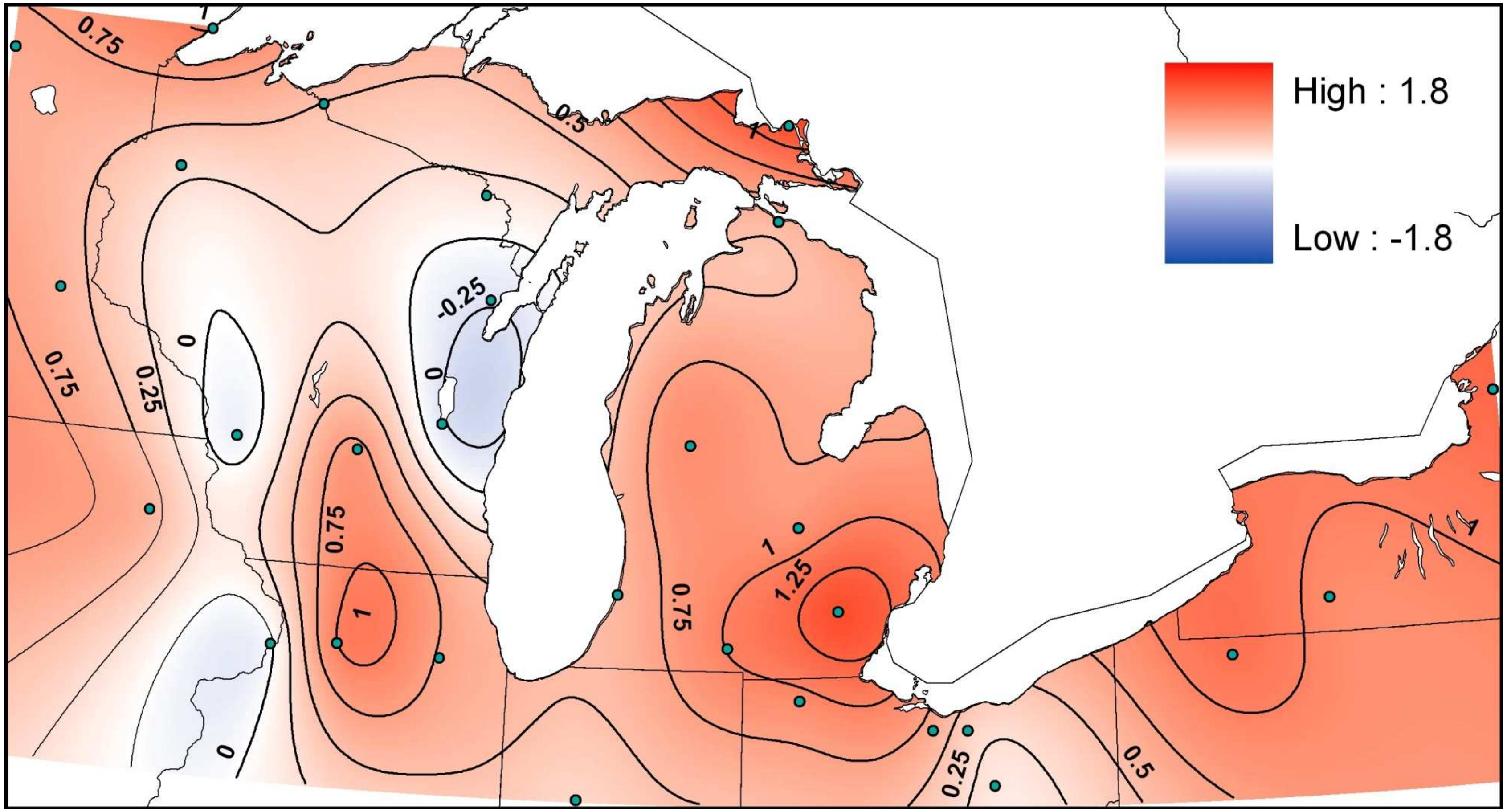

Figure 29: Rate of change of Percolation. Average of all soils, Wheat land cover (mm/year). Contours are 0.25 mm/year.

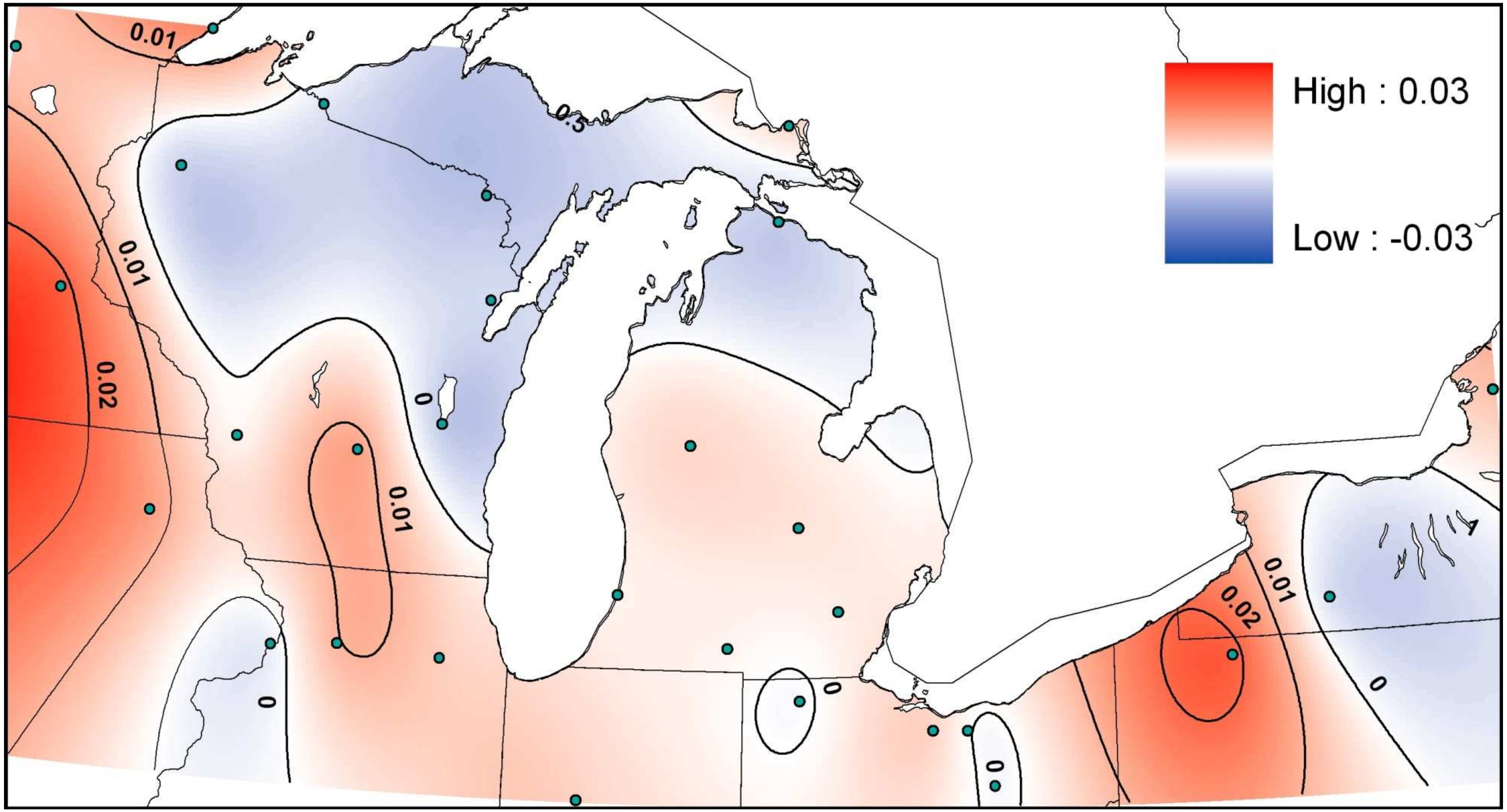

Figure 30: Rate of change, return of soil moisture from shallow aquifer. Average of all soils, Corn land cover (mm/year). Contours are 0.01 mm/year.

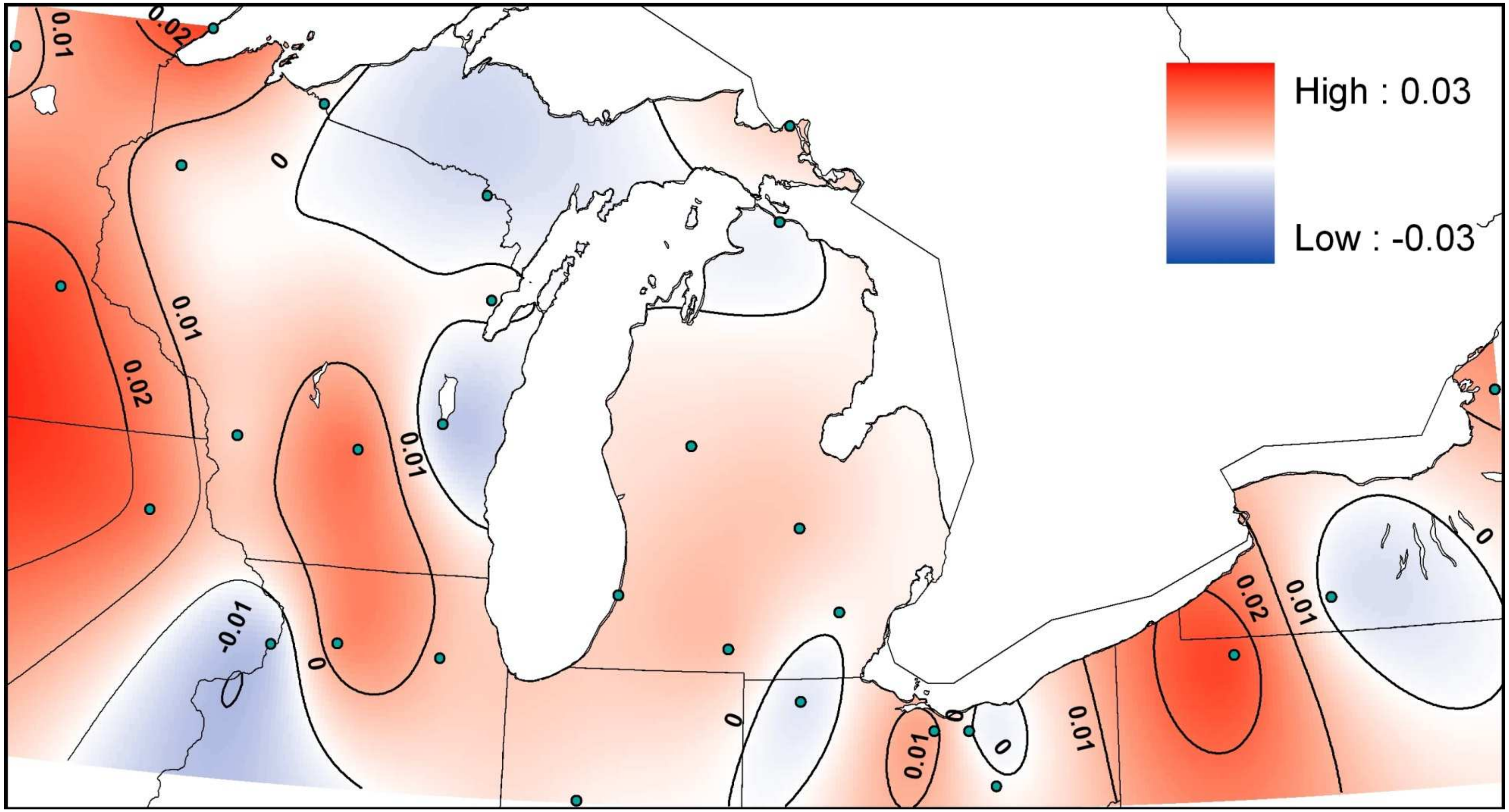

Figure 31: Rate of change, return of soil moisture from shallow aquifer. Average of all soils, Forest land cover (mm/year). Contours are 0.01 mm/year.

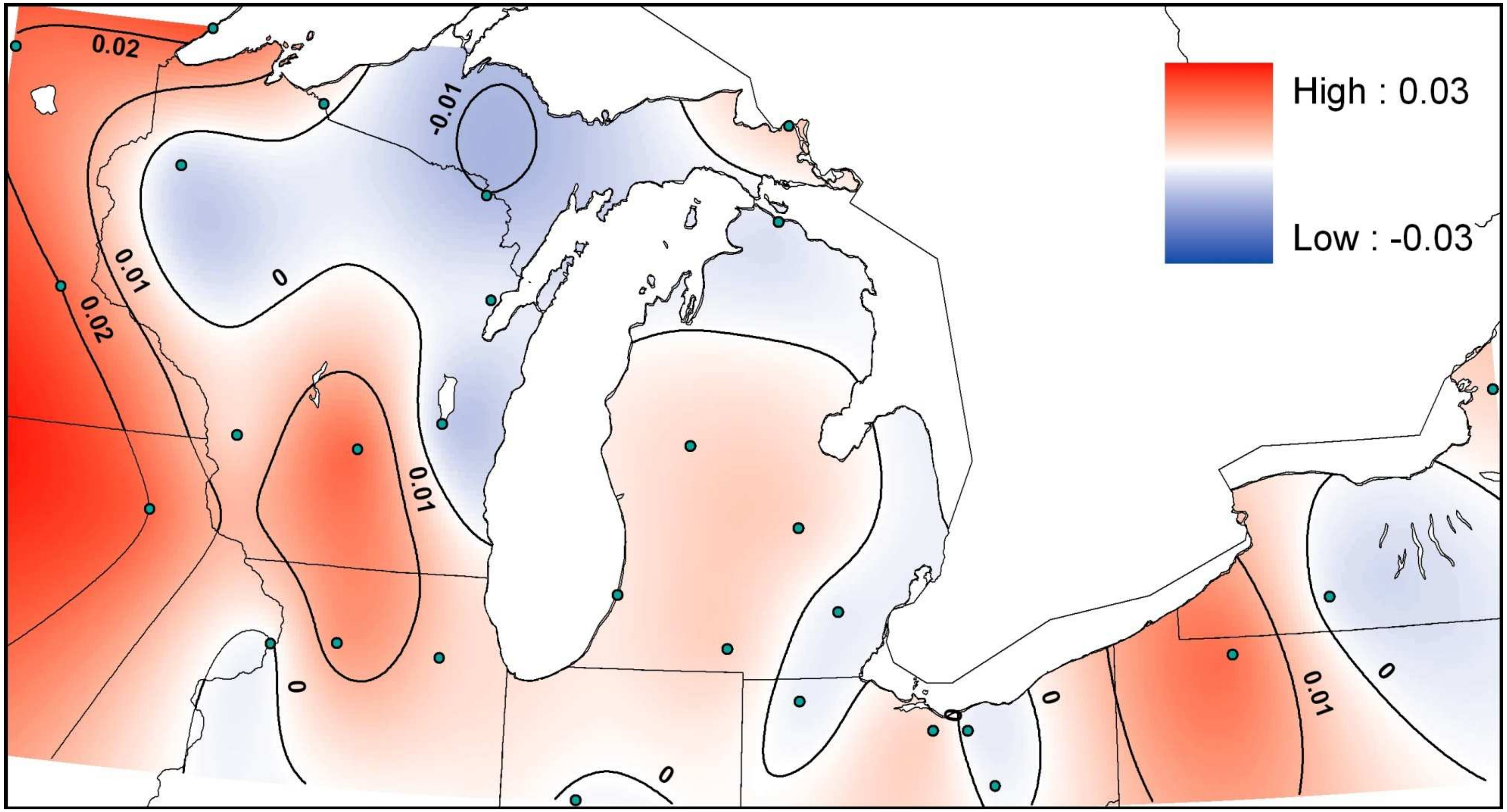

Figure 32: Rate of change, return of soil moisture from shallow aquifer. Average of all soils, Pasture land cover (mm/year). Contours are 0.01 mm/year.

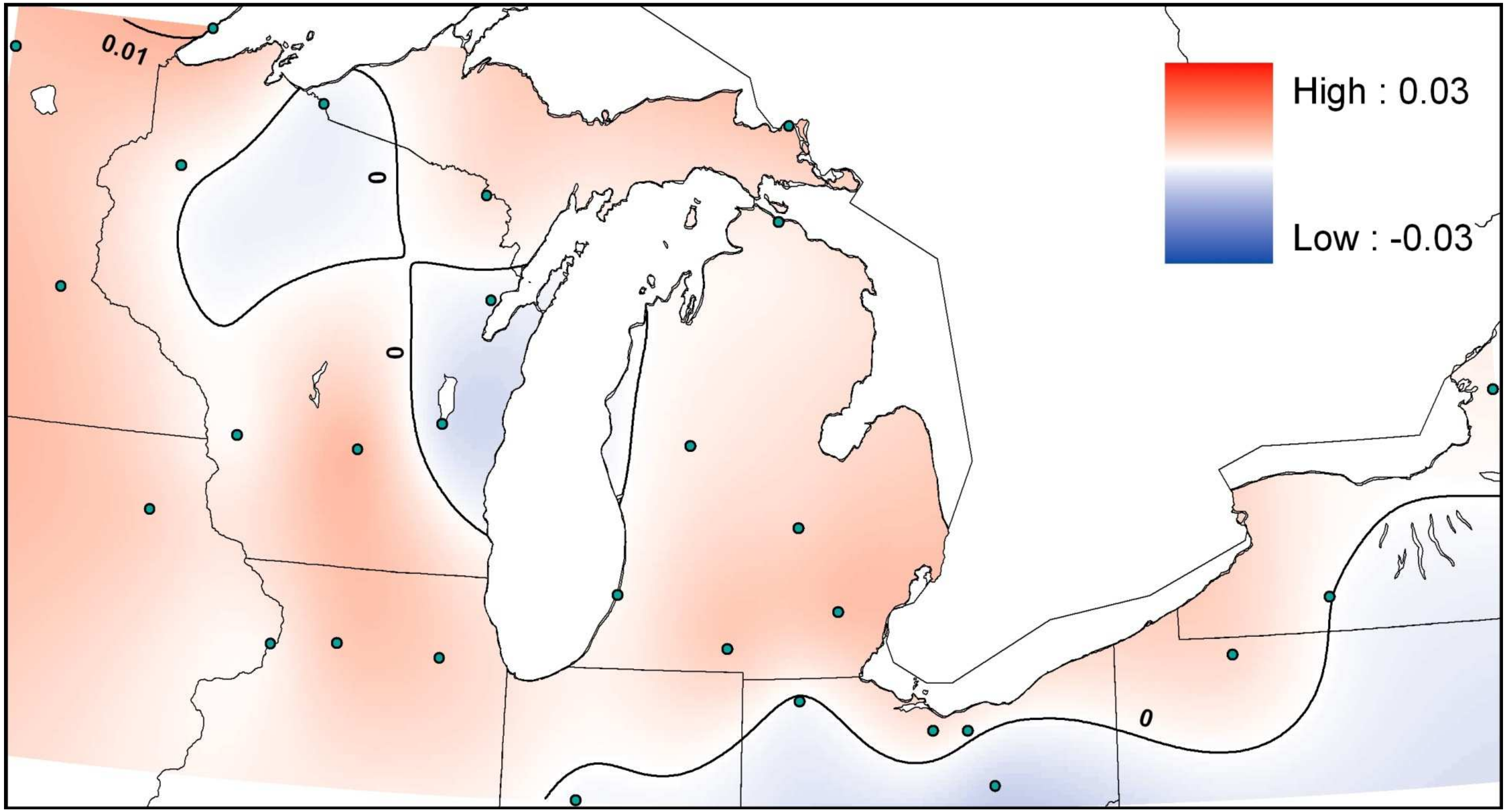

Figure 33: Rate of change, return of soil moisture from shallow aquifer. Average of all soils, Urban land cover (mm/year). Contours are 0.01 mm/year.

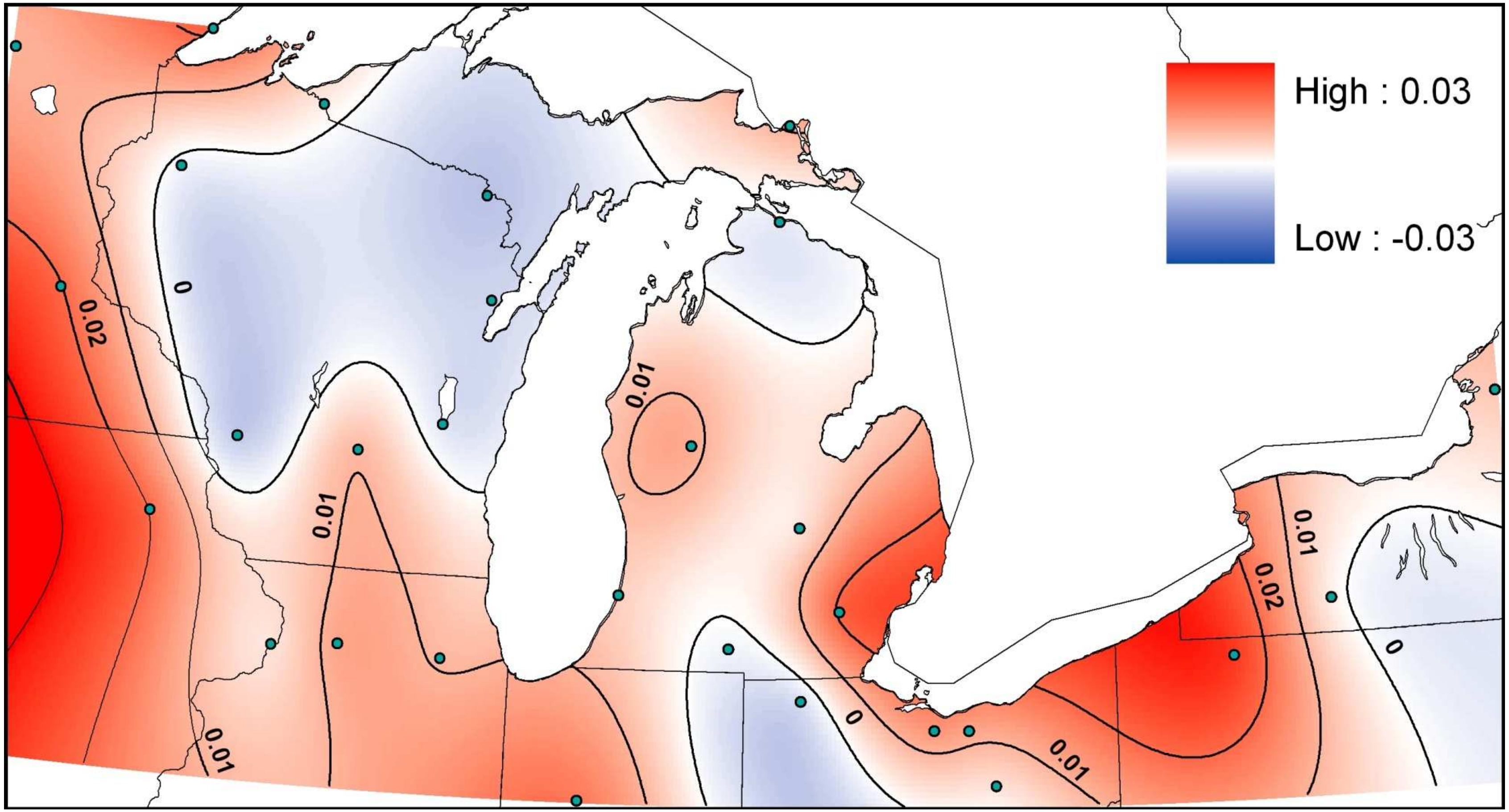

Figure 34: Rate of change, return of soil moisture from shallow aquifer. Average of all soils, Wheat land cover (mm/year). Contours are 0.01 mm/year.

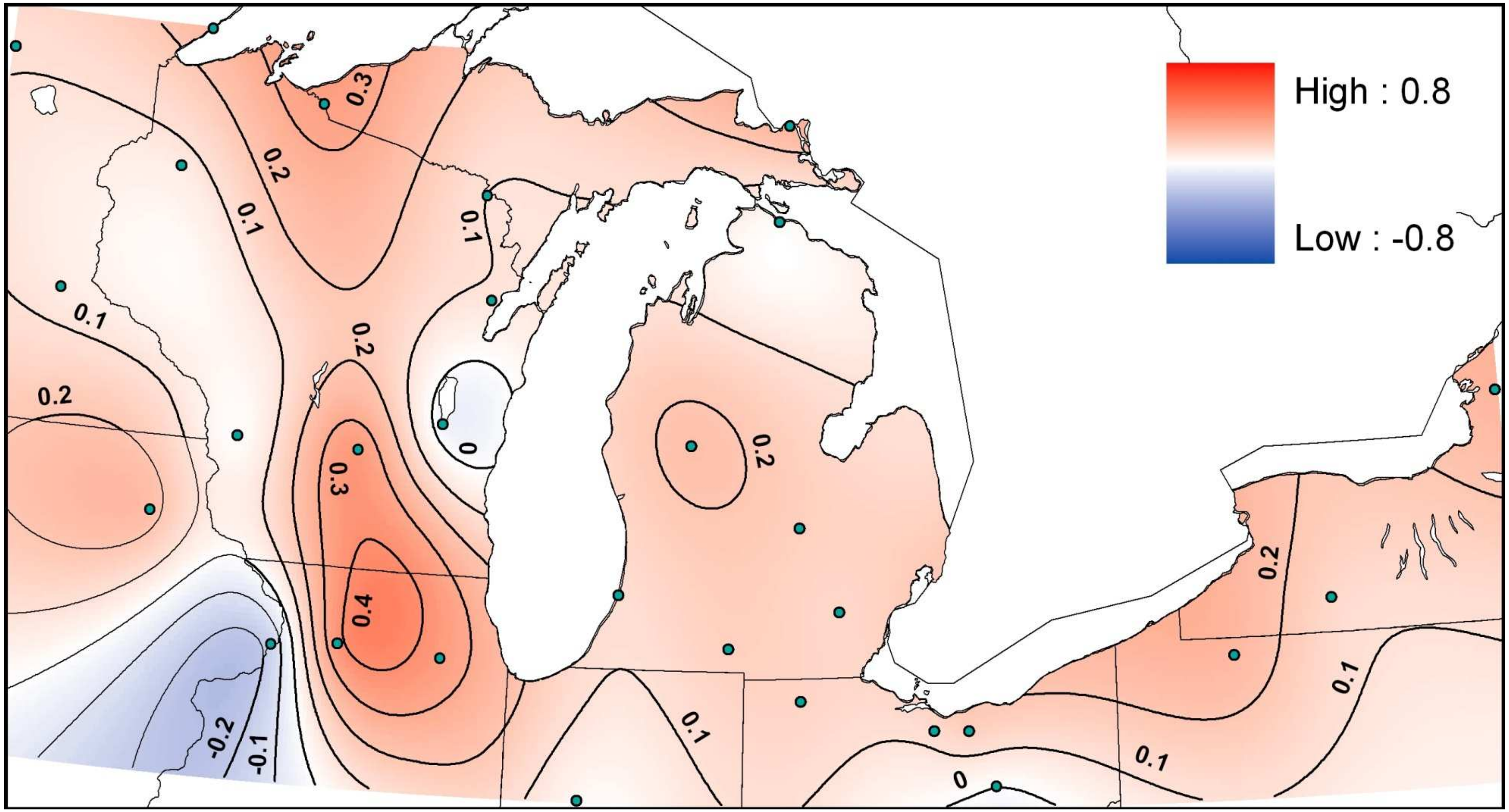

Figure 35: Rate of change, Runoff. Average of all soils, Corn land cover (mm/year). Contours are 0.1 mm/year.

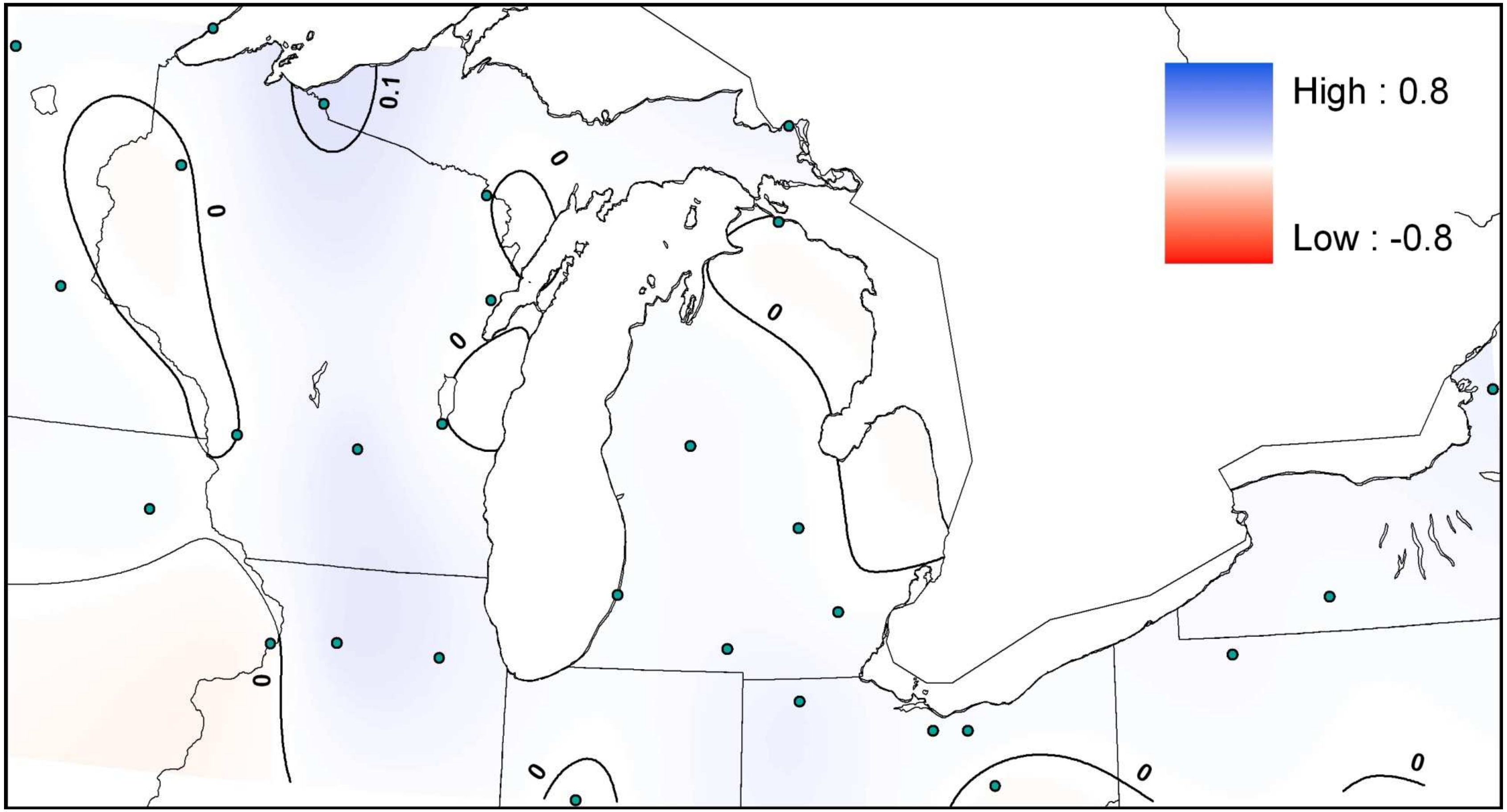

Figure 36: Rate of change, Runoff. Average of all soils, Pasture land cover (mm/year). Contours are 0.1 mm/year.

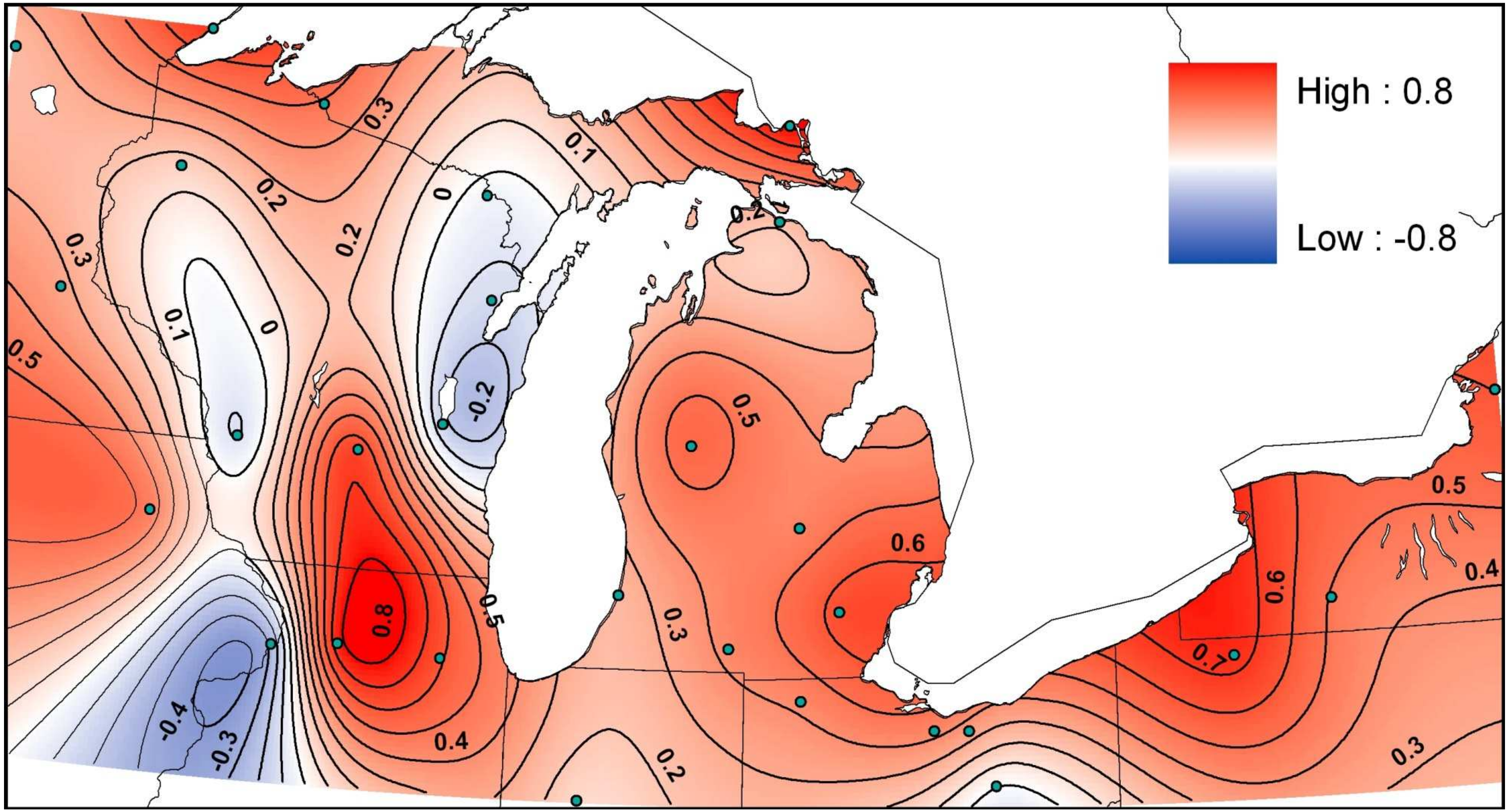

Figure 37: Rate of change, Runoff. Average of all soils, Urban land cover (mm/year). Contours are 0.1 mm/year.

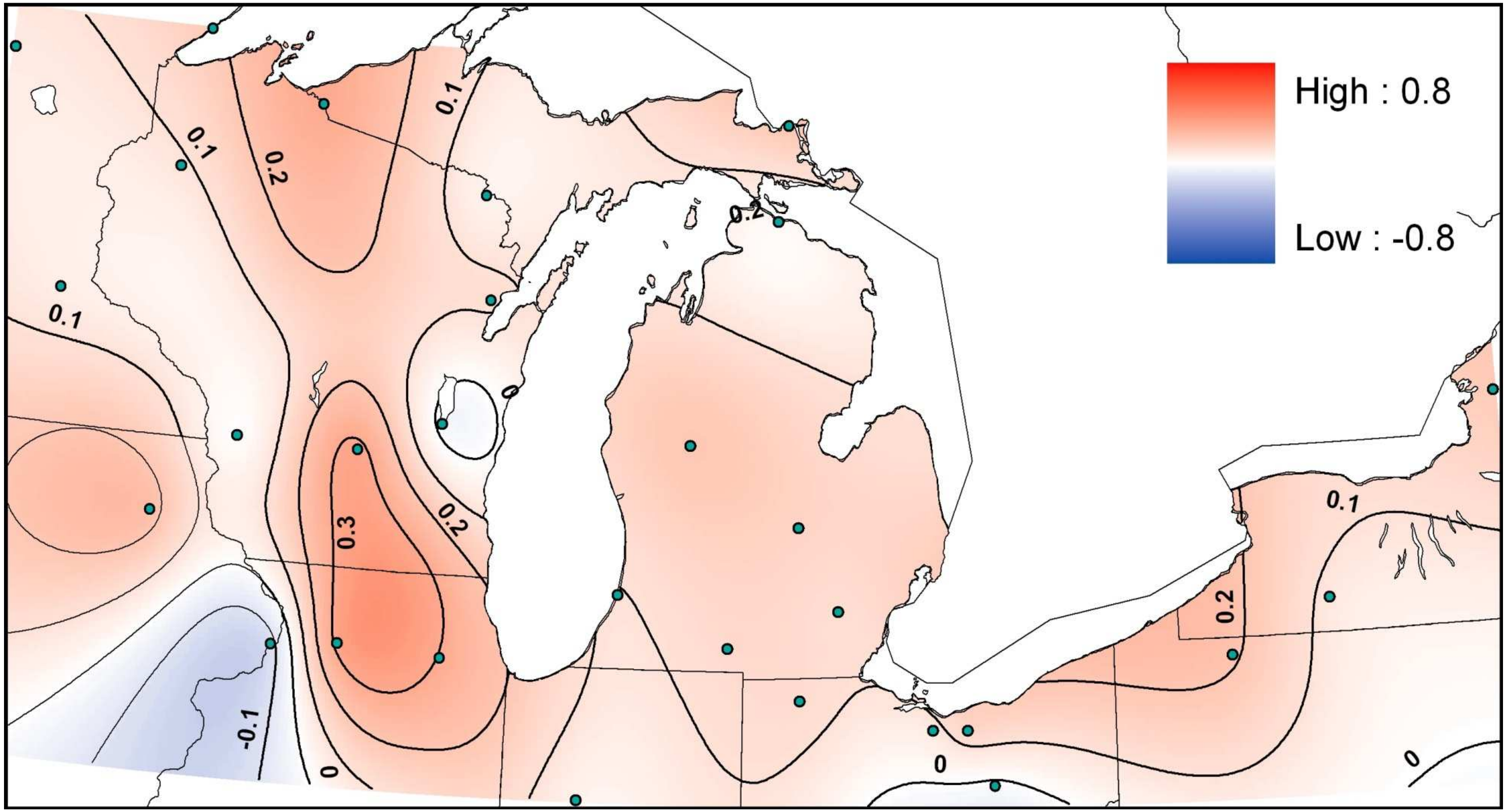

Figure 38: Rate of change, Runoff. Average of all soils, Wheat land cover (mm/year). Contours are 0.1 mm/year.

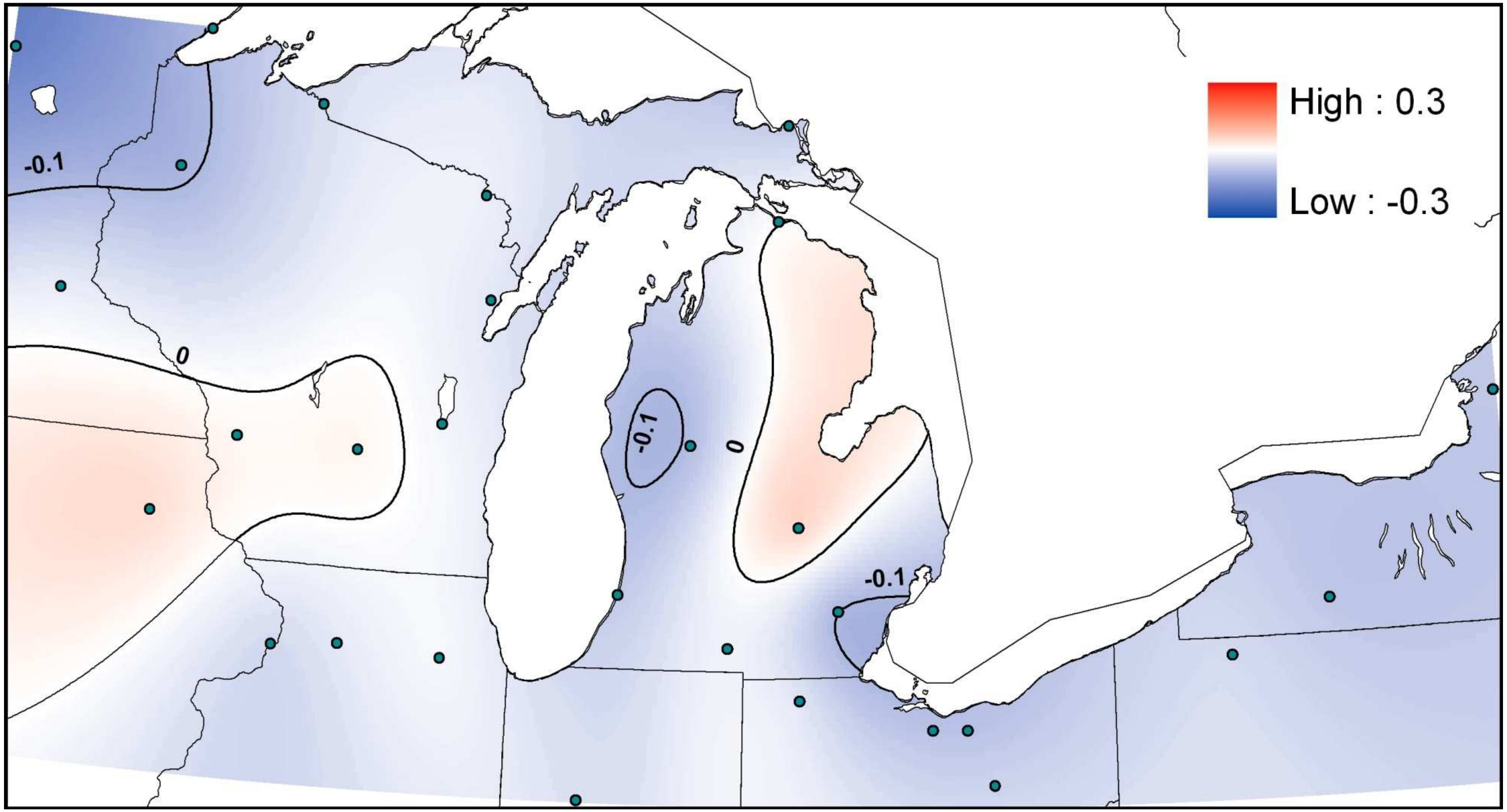

Figure 39: Rate of change, Day of Year of the beginning of soil water discharge. Average of SL, L, and SiL. Corn land cover (days/year). Contours are 0.1 days/year.

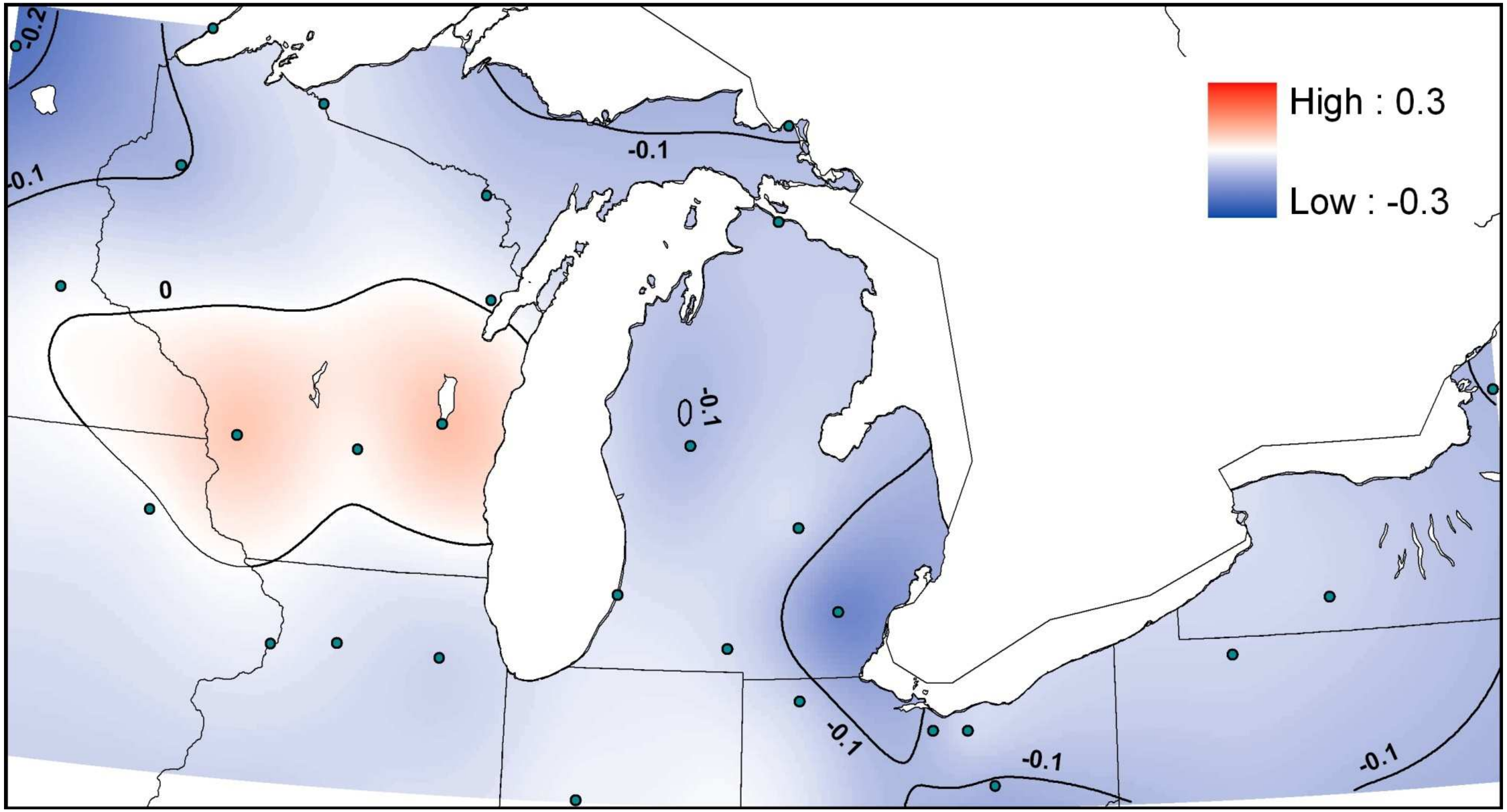

Figure 40: Rate of change, Day of Year of the beginning of soil water discharge. Average of SL, L, and SiL. Forest land cover (days/year). Contours are 0.1 days/year.

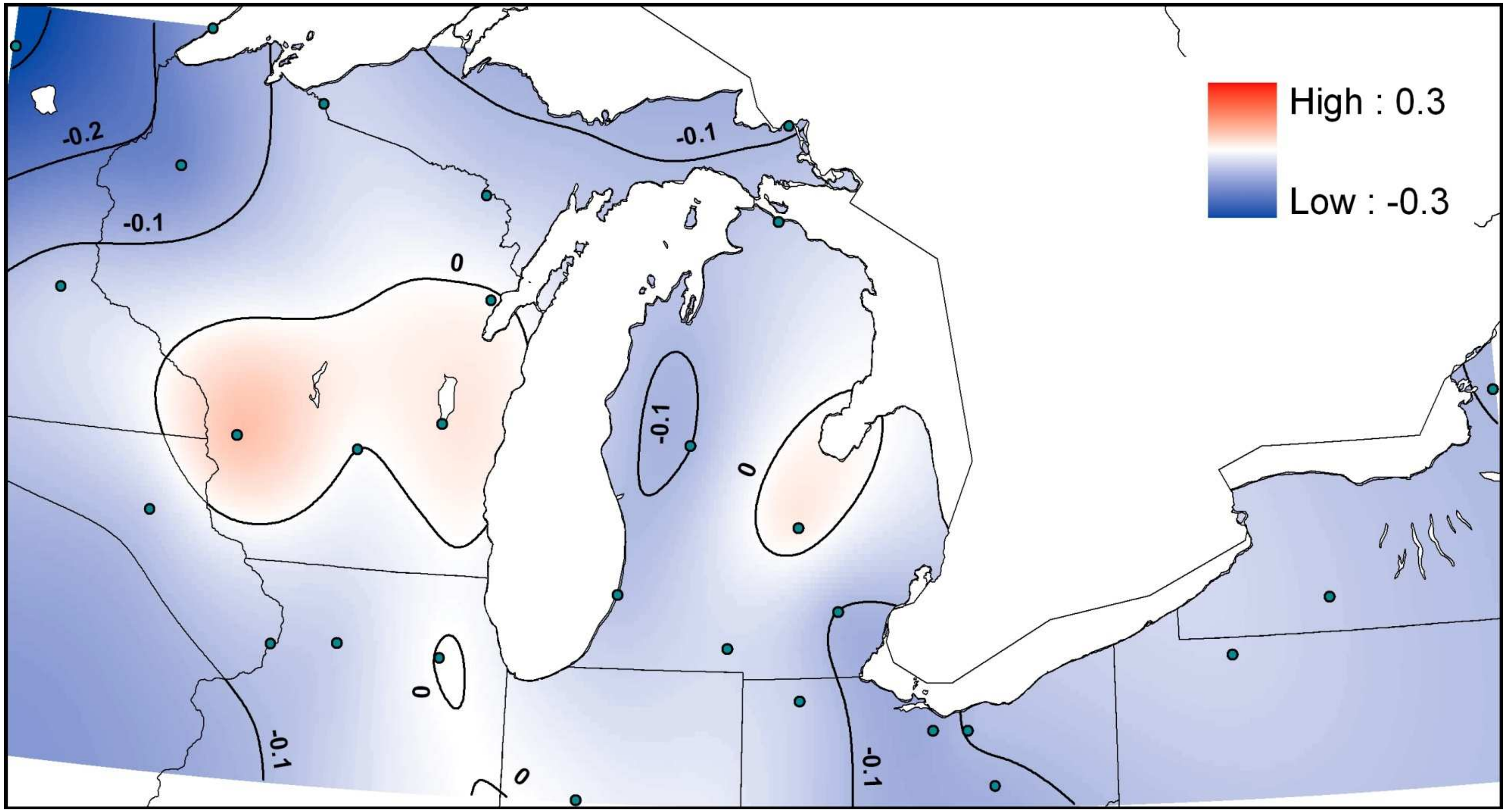

Figure 41: Rate of change, Day of Year of the beginning of soil water discharge. Average of SL, L, and SiL. Pasture land cover (days/year). Contours are 0.1 days/year.

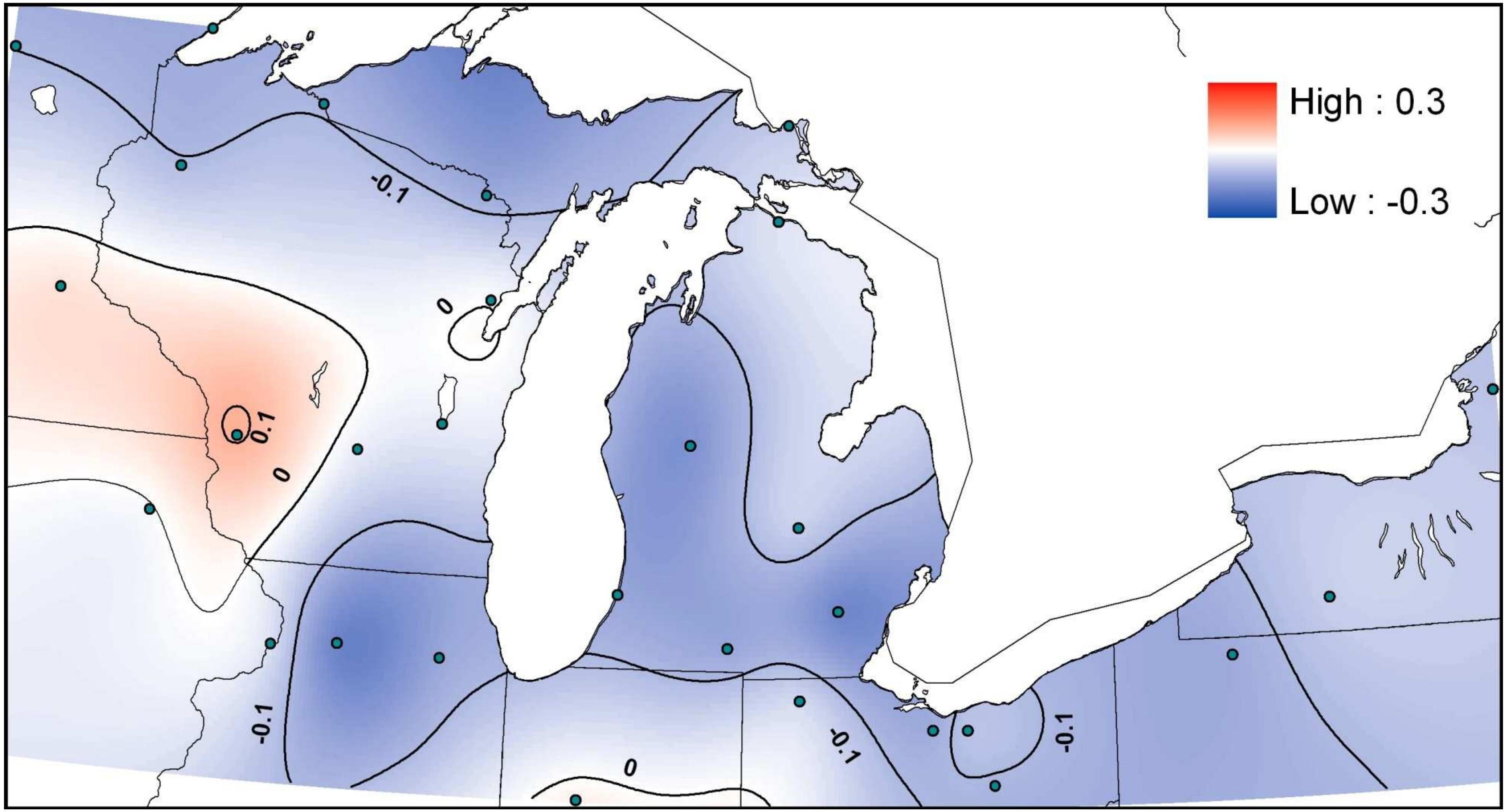

Figure 42: Rate of change, Day of Year of the beginning of soil water discharge. Average of SL, L, and SiL. Urban land cover (days/year). Contours are 0.1 days/year.

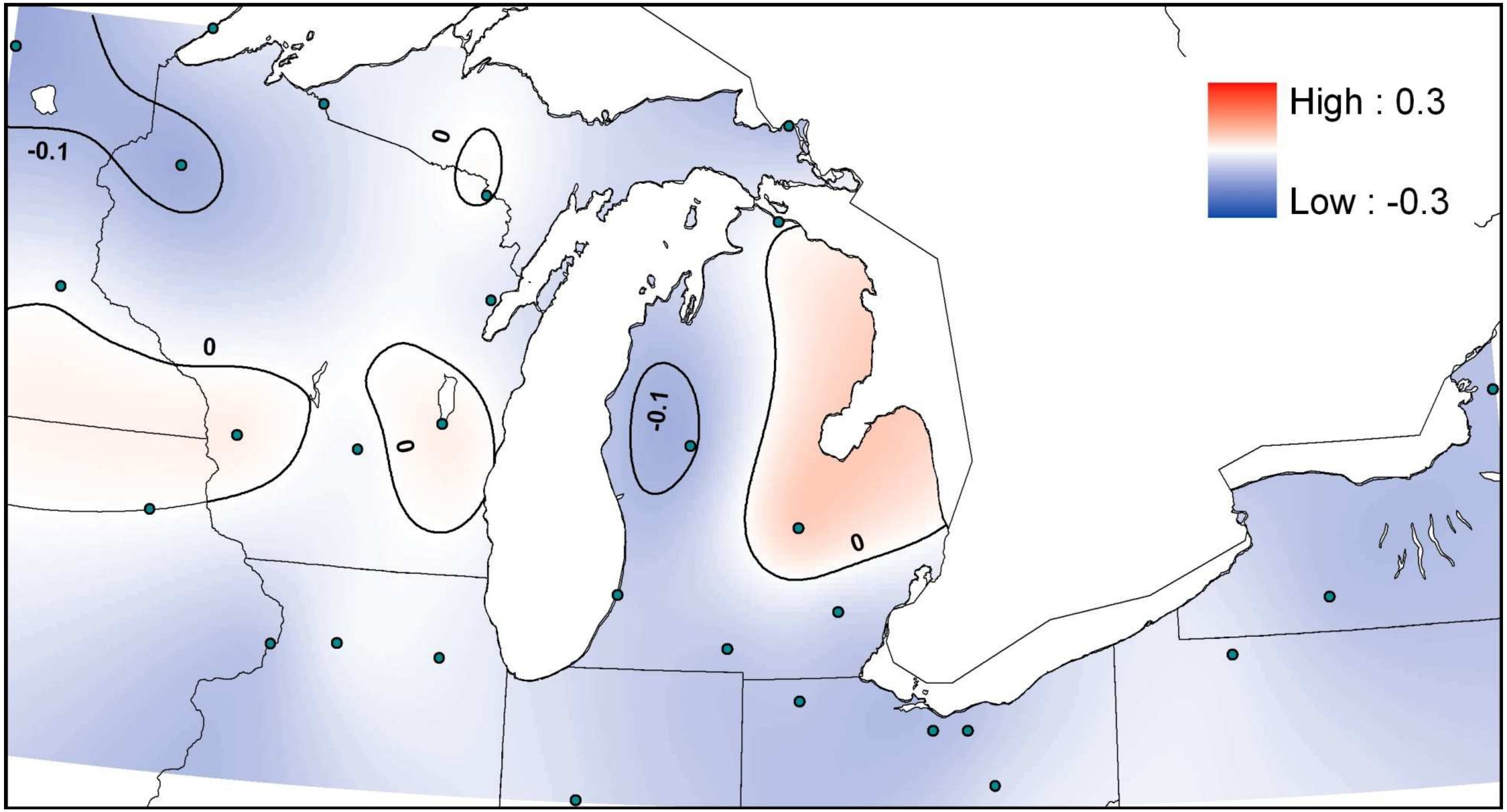

Figure 43: Rate of change, Day of Year of the beginning of soil water discharge. Average of SL, L, and SiL. Wheat land cover (days/year). Contours are 0.1 days/year.

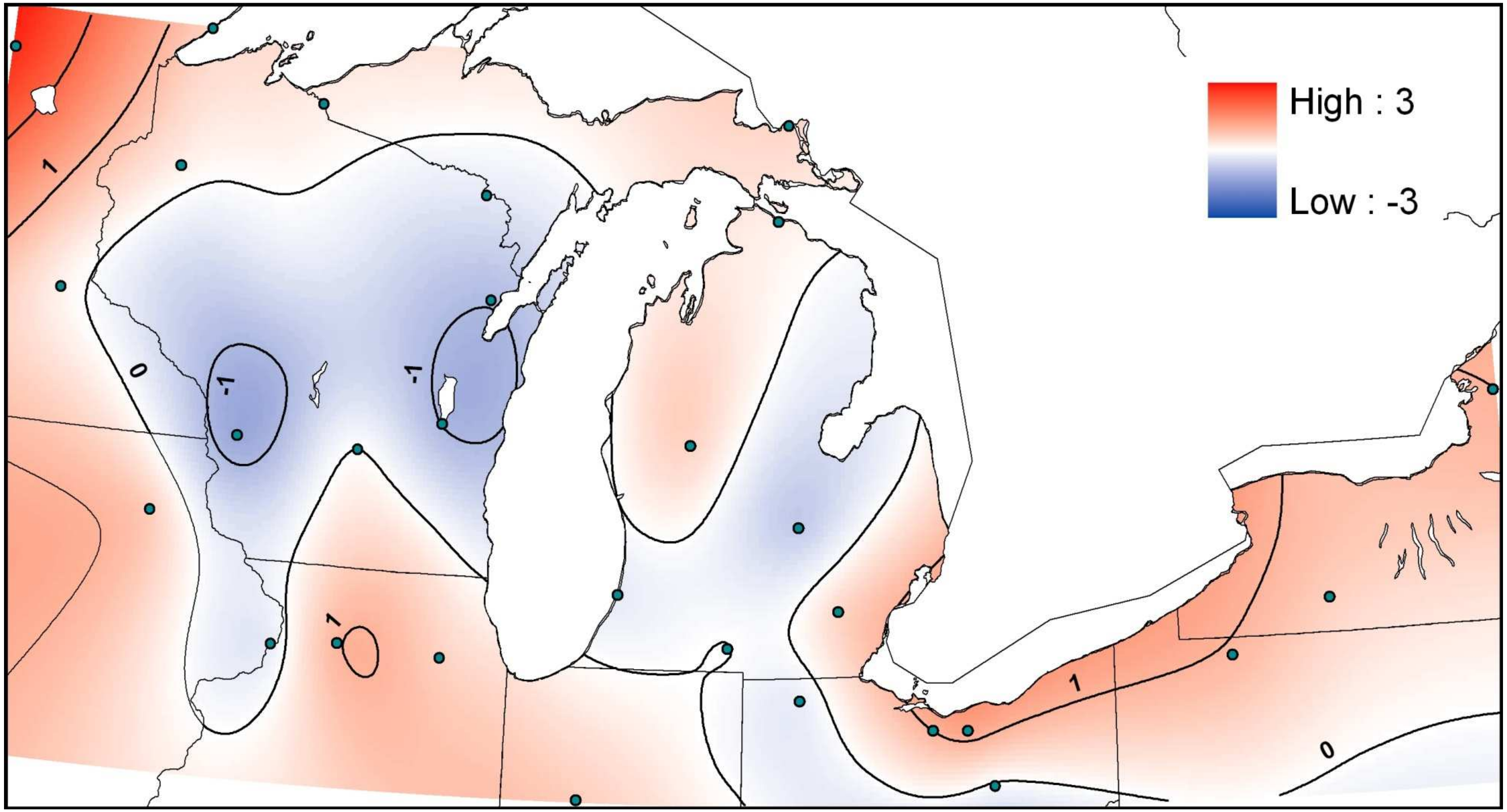

Figure 44: Rate of change, Rate of soil water discharge. Average of SL, L, and SiL. Corn land cover (μm/(days*year)). Contours are μm /(days/year).

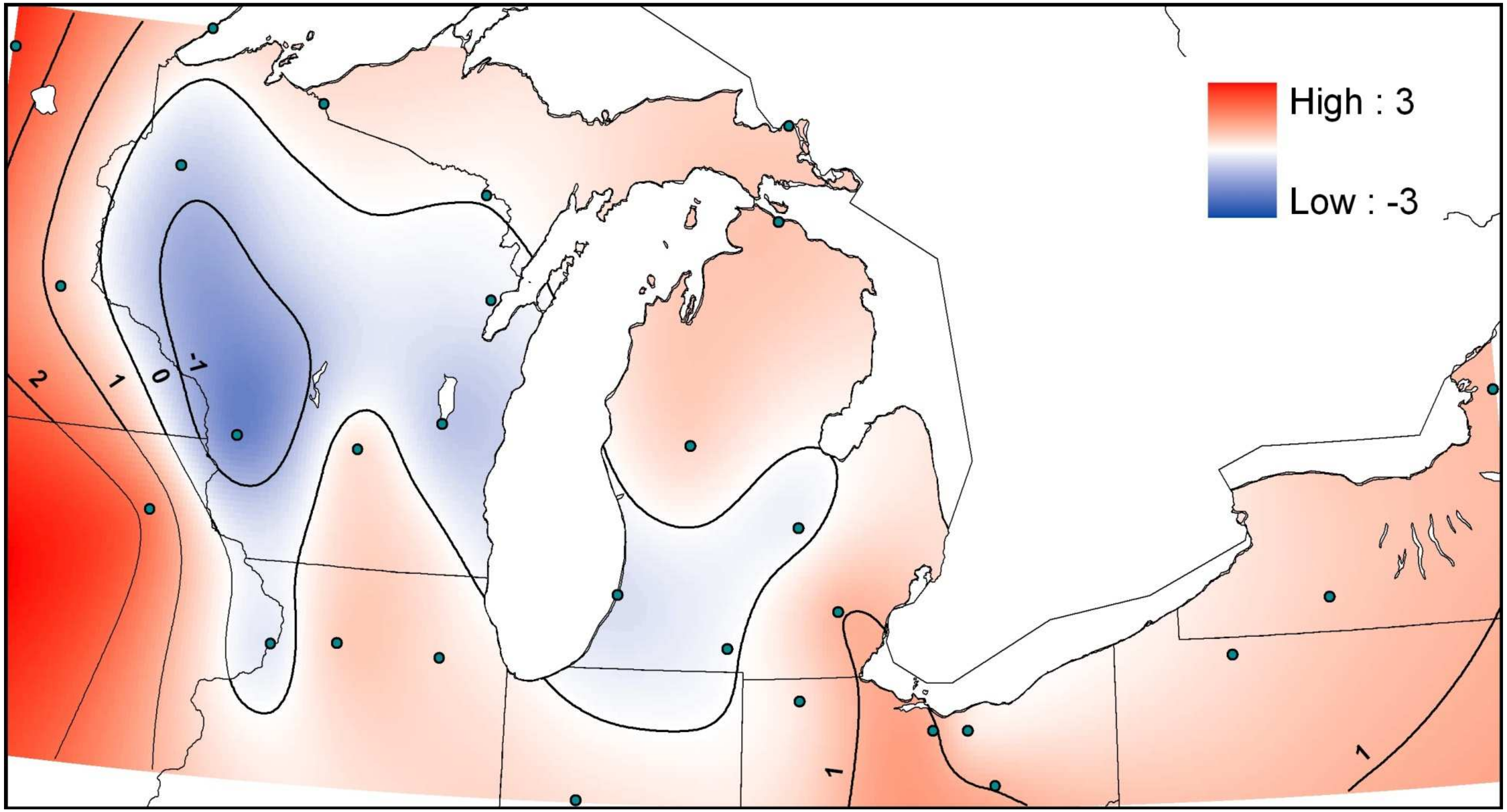

Figure 45: Rate of change, Rate of soil water discharge. Average of SL, L, and SiL. Forest land cover (μm/(days*year)). Contours are μm /(days/year).

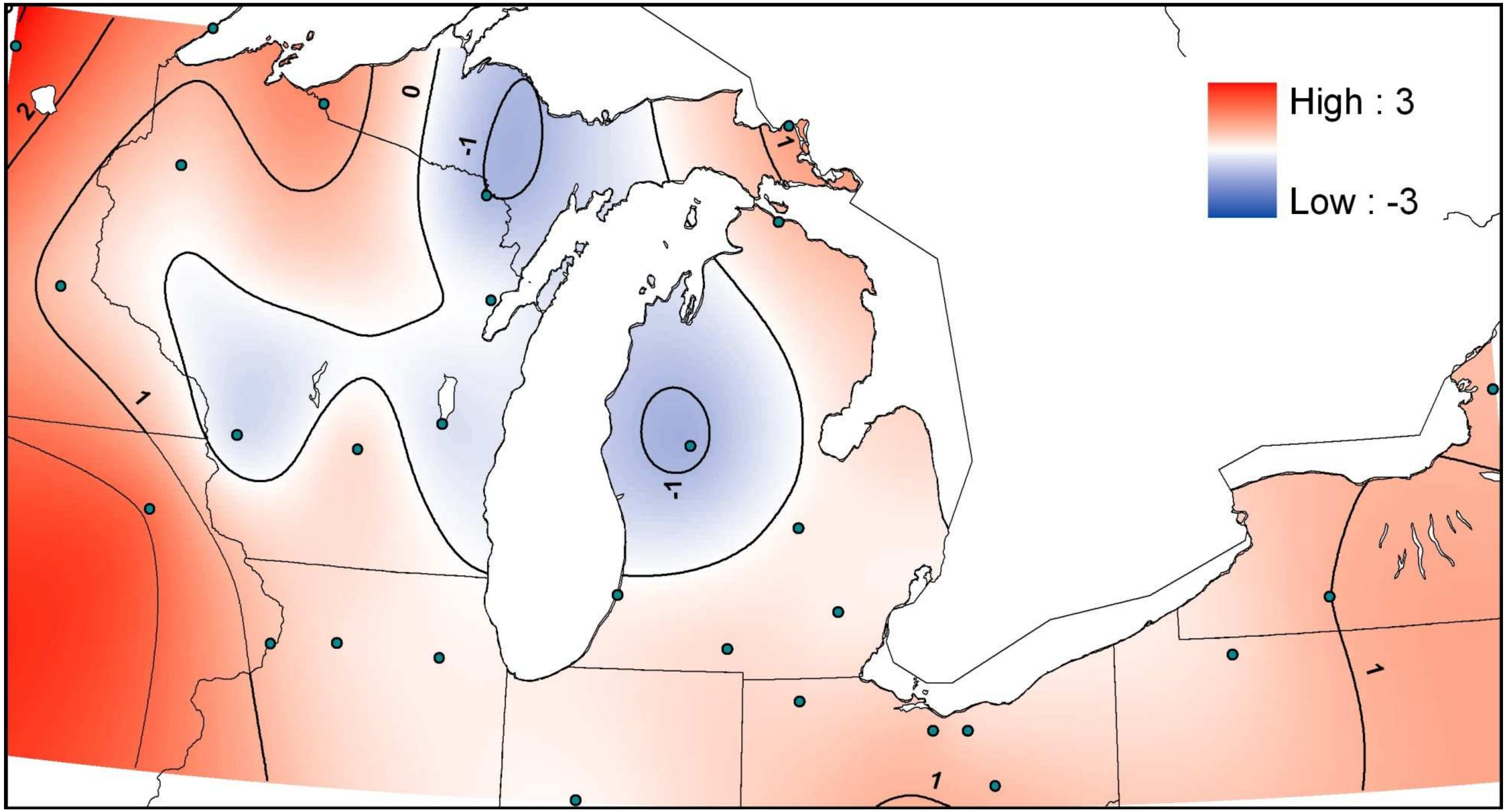

Figure 46: Rate of change, Rate of soil water discharge. Average of SL, L, and SiL. Pasture land cover (μm/(days*year)). Contours are μm /(days/year).

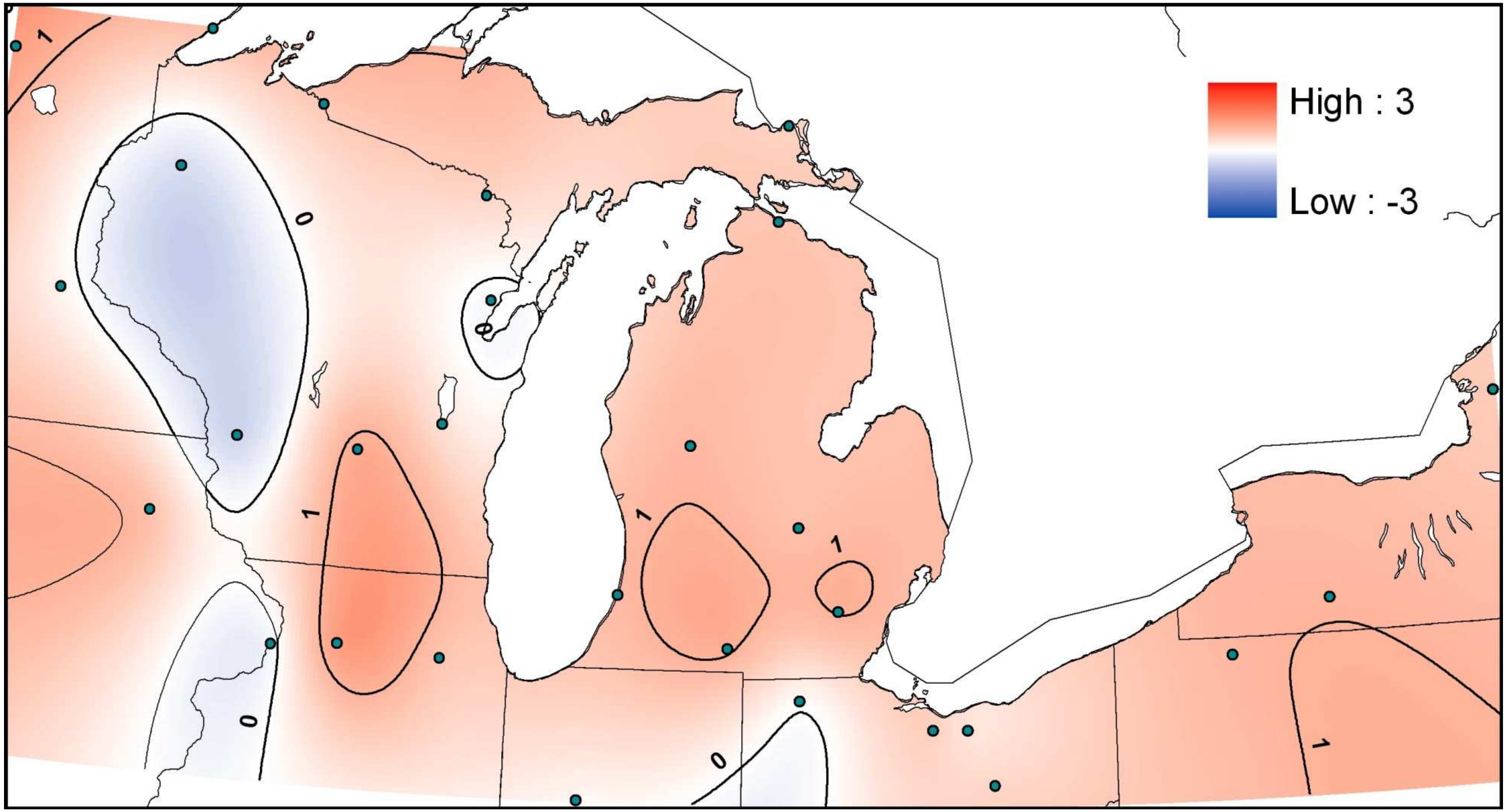

Figure 47: Rate of change, Rate of soil water discharge. Average of SL, L, and SiL. Urban land cover (μm/(days*year)). Contours are μm /(days/year).

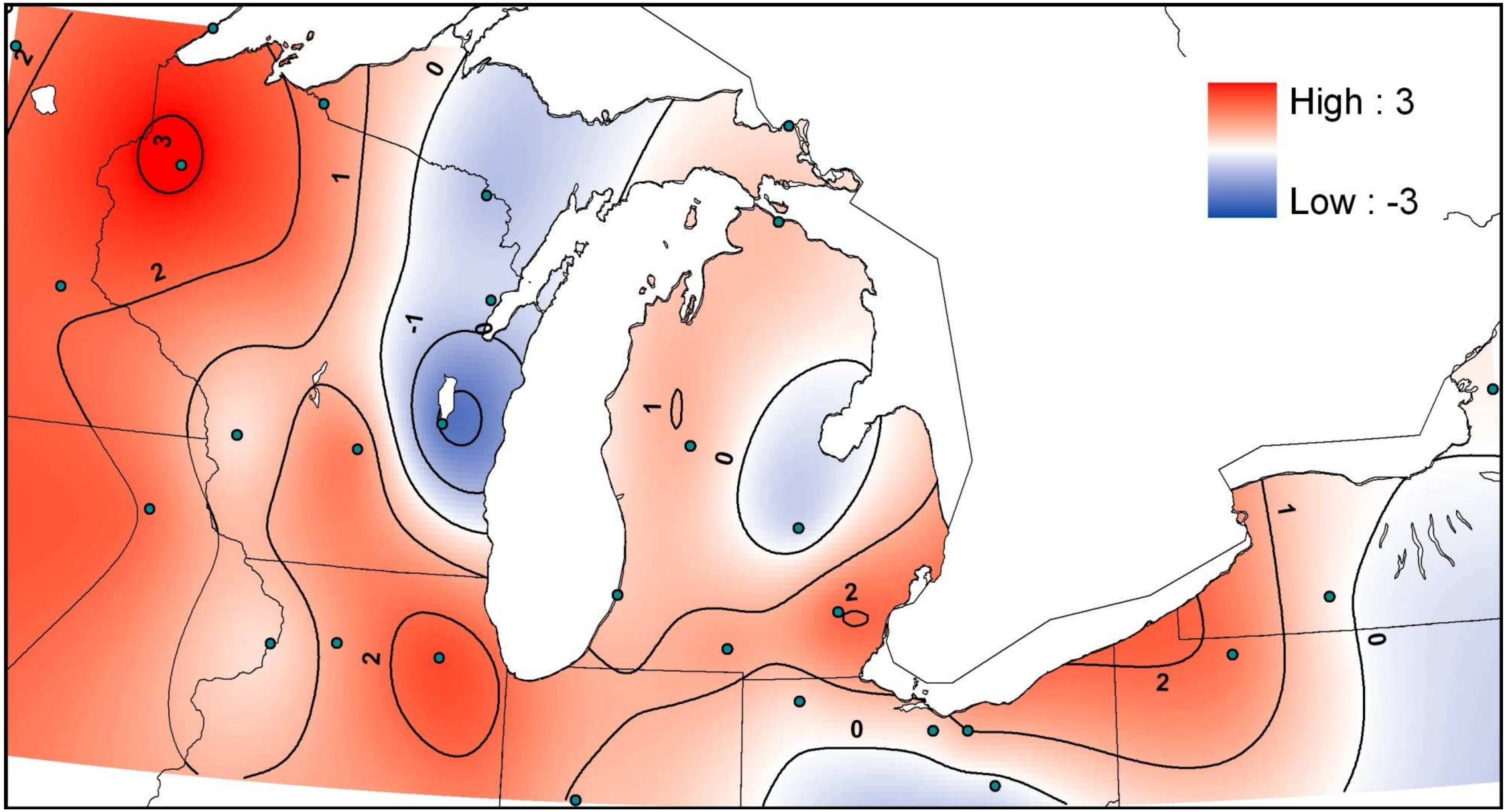

Figure 48: Rate of change, Rate of soil water discharge. Average of SL, L, and SiL. Wheat land cover (μm/(days*year)). Contours are μm /(days/year).

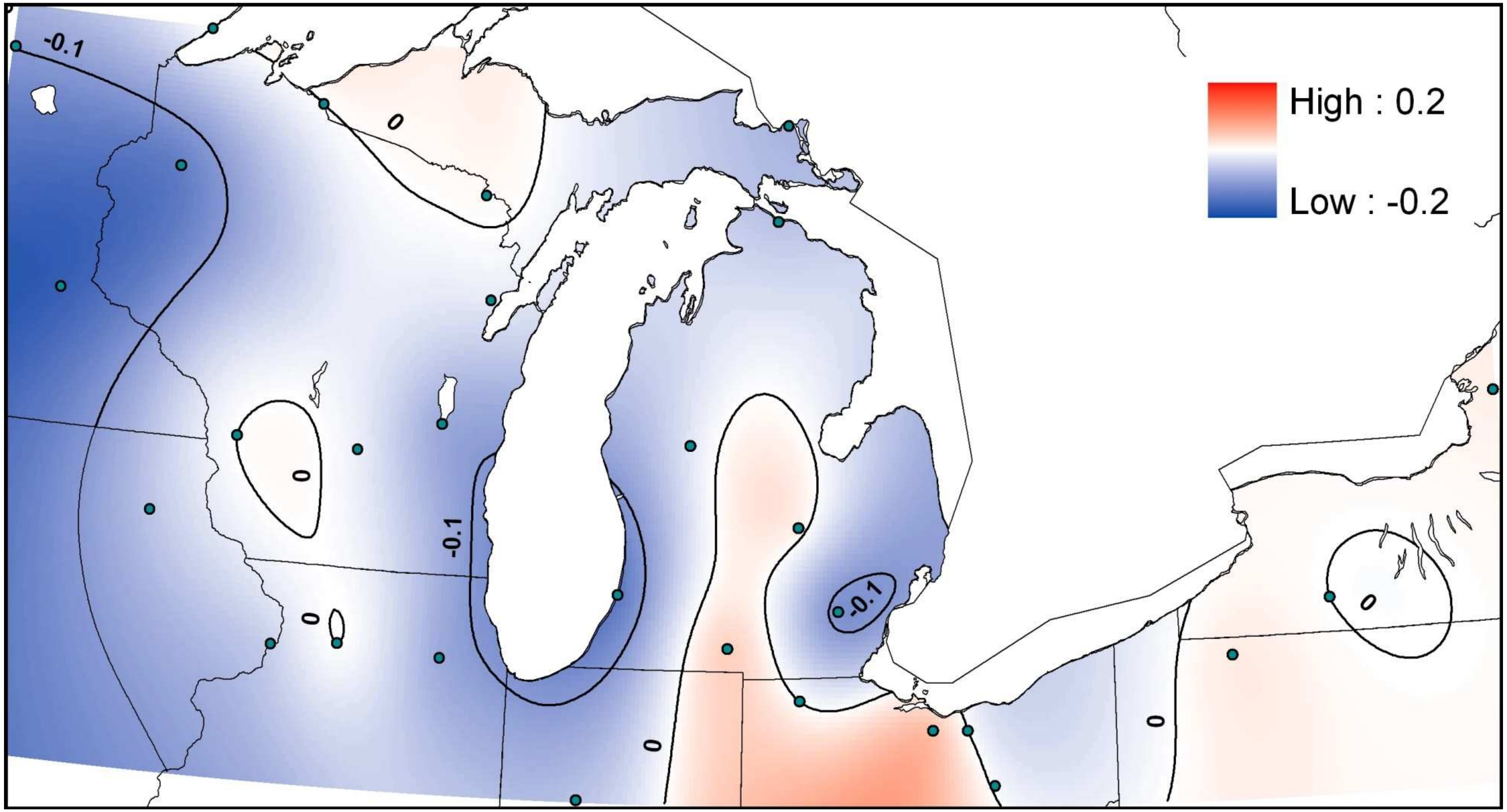

Figure 49: Rate of change, Day of Year of Minimum Soil Moisture. Average of SL, L, and SiL. Corn land cover, days/year. Contours are 0.1 days/year.

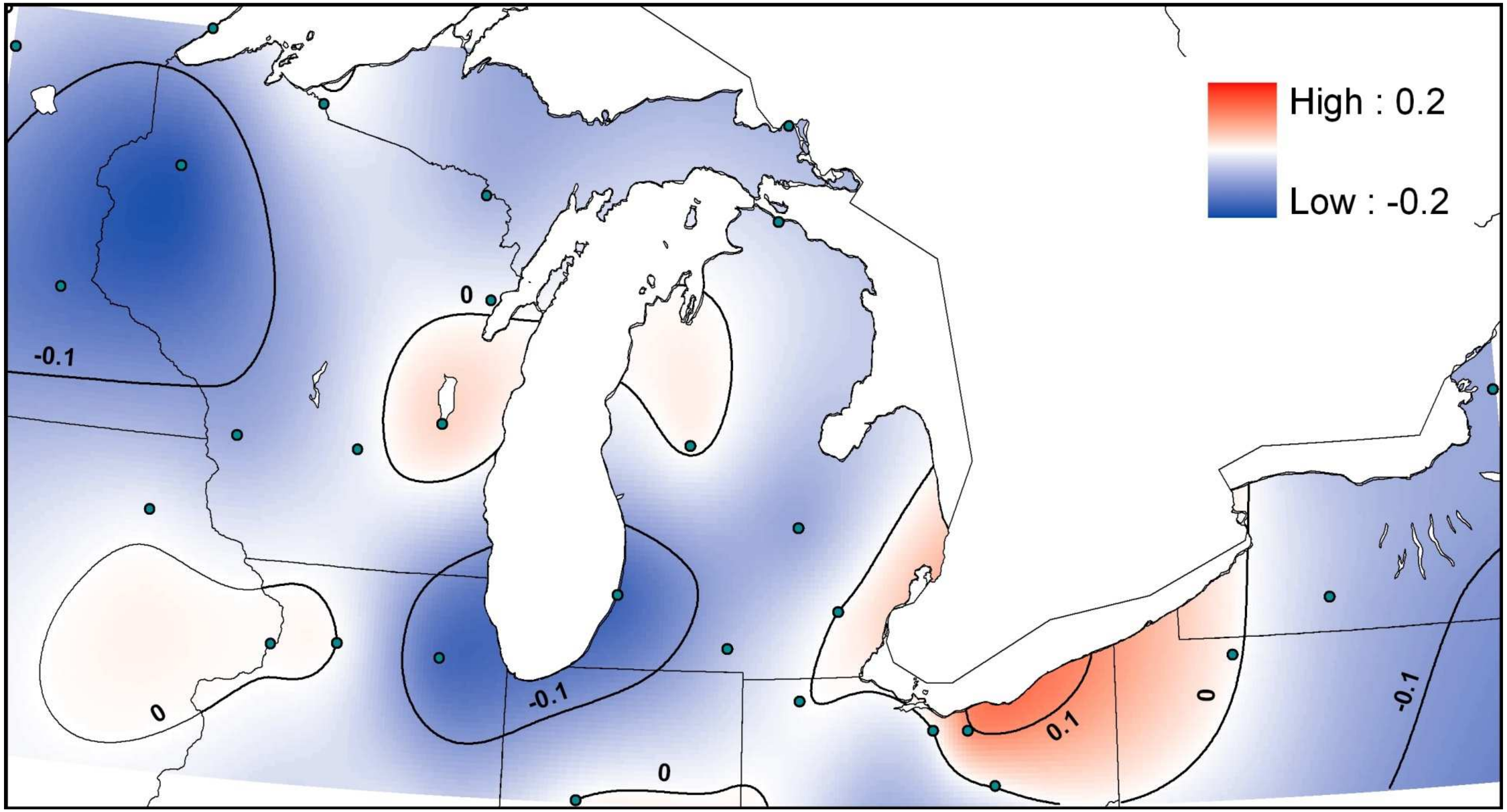

Figure 50: Rate of change, Day of Year of Minimum Soil Moisture. Average of SL, L, and SiL. Forest land cover, days/year. Contours are 0.1 days/year.

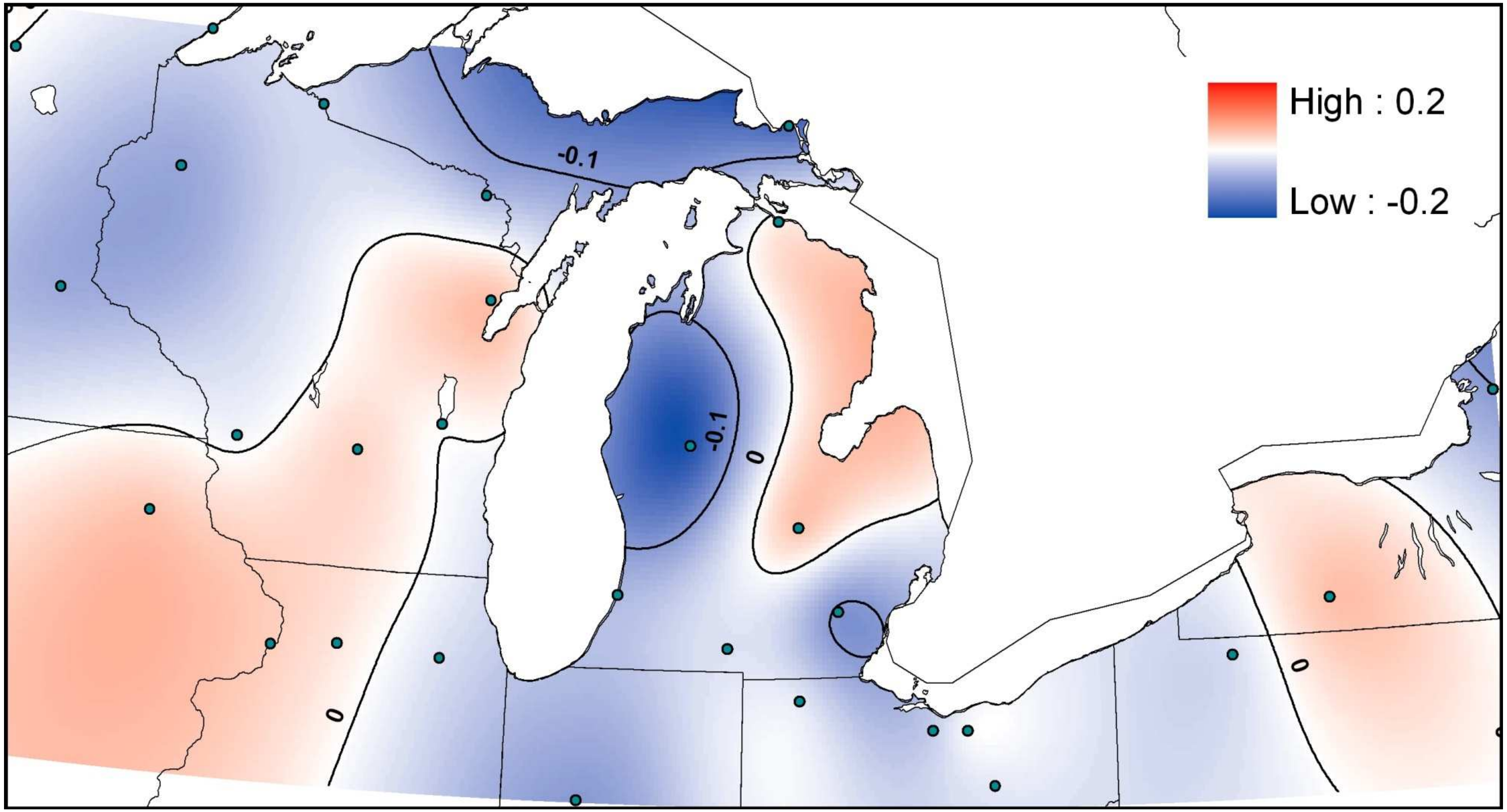

Figure 51: Rate of change, Day of Year of Minimum Soil Moisture. Average of SL, L, and SiL. Pasture land cover, days/year. Contours are 0.1 days/year.

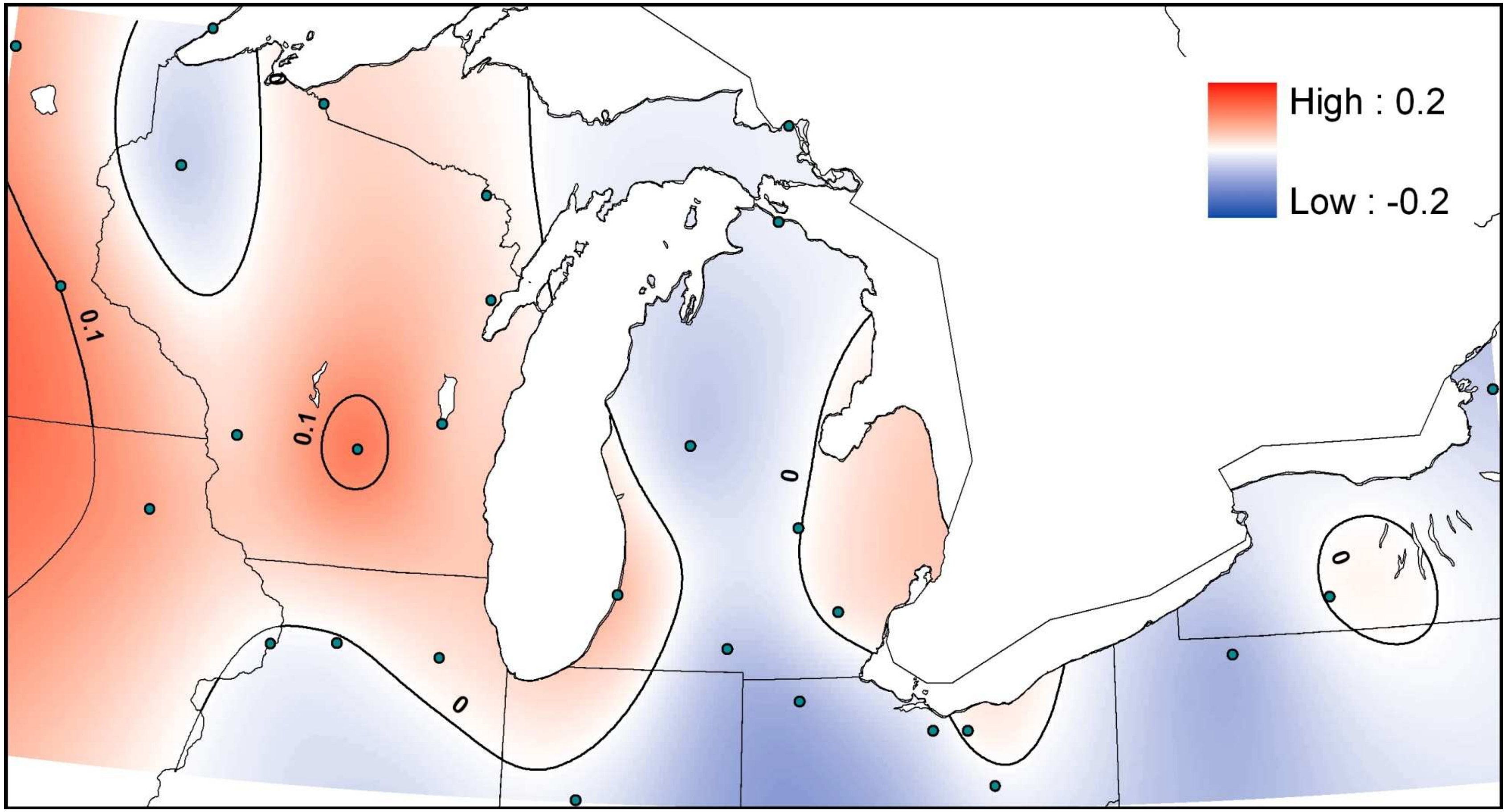

Figure 52: Rate of change, Day of Year of Minimum Soil Moisture. Average of SL, L, and SiL. Urban land cover, days/year. Contours are 0.1 days/year.

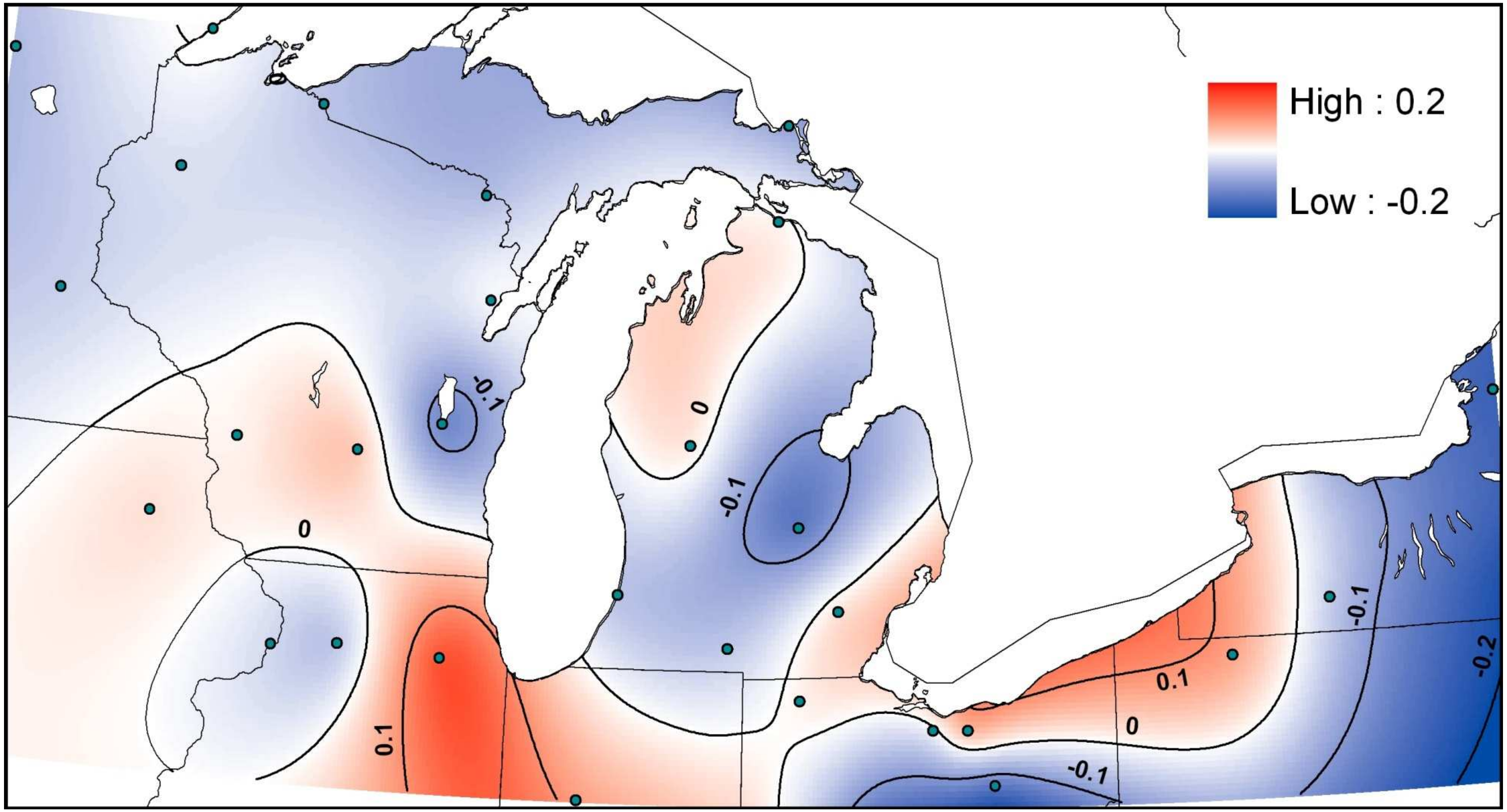

Figure 53: Rate of change, Day of Year of Minimum Soil Moisture. Average of SL, L, and SiL. Wheat land cover, days/year. Contours are 0.1 days/year.

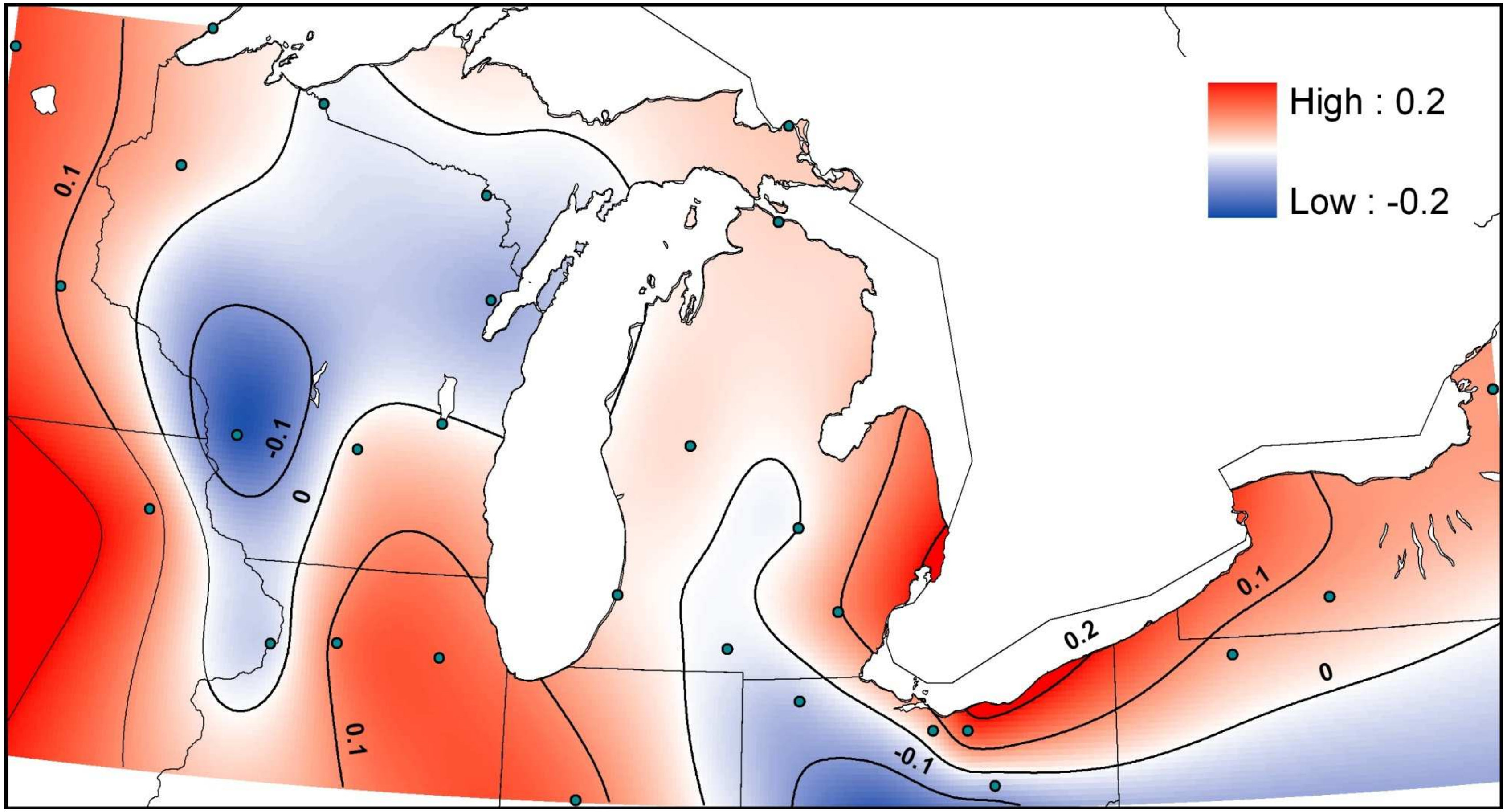

Figure 54: Rate of change, Minimum Yearly Soil Moisture value. Average of SL, L, and SiL, Corn land cover, mm/year. Contours are 0.1 mm/year.

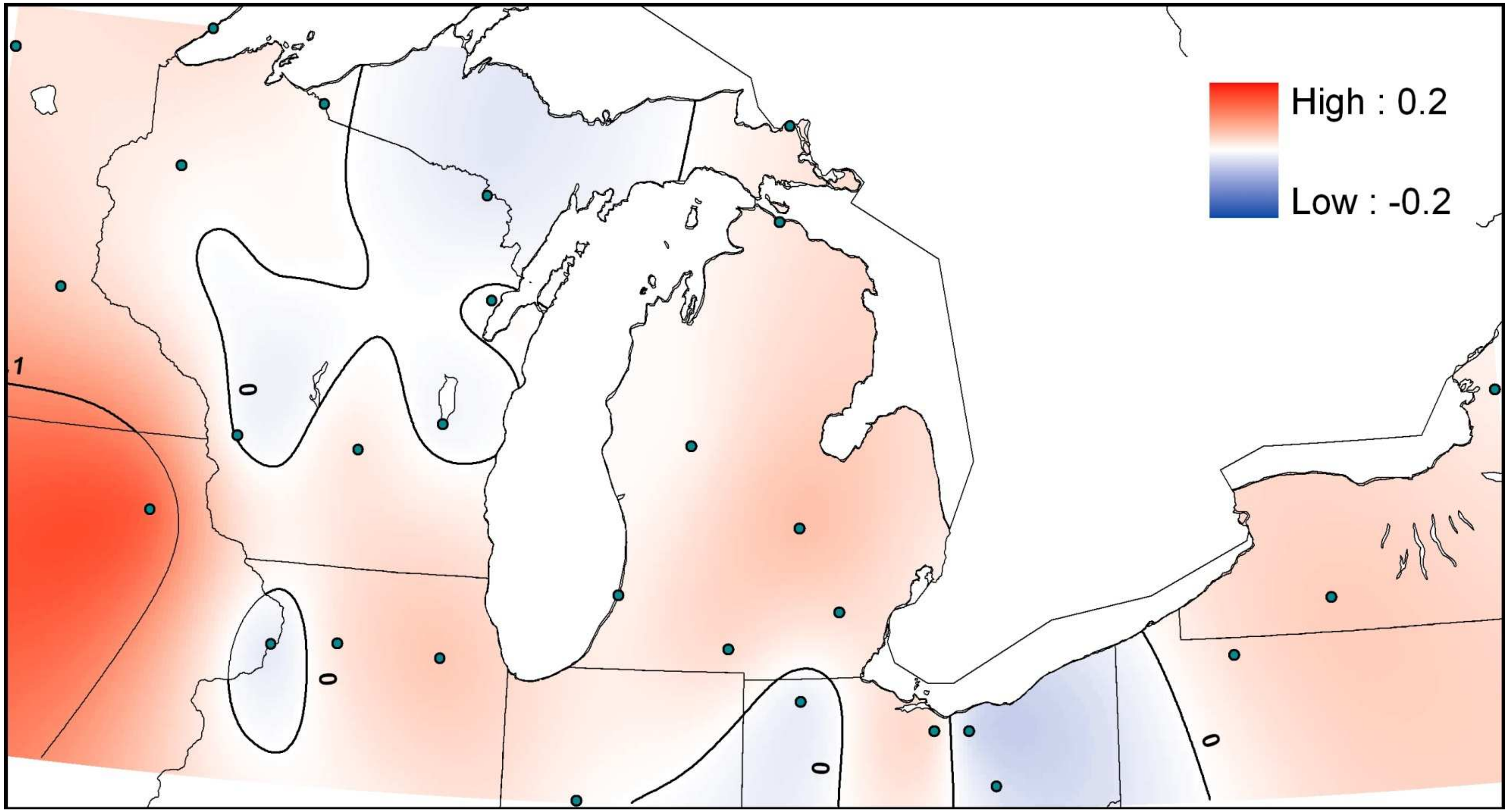

Figure 55: Rate of change, Minimum Yearly Soil Moisture value. Average of SL, L, and SiL, Forest land cover, mm/year. Contours are 0.1 mm/year.

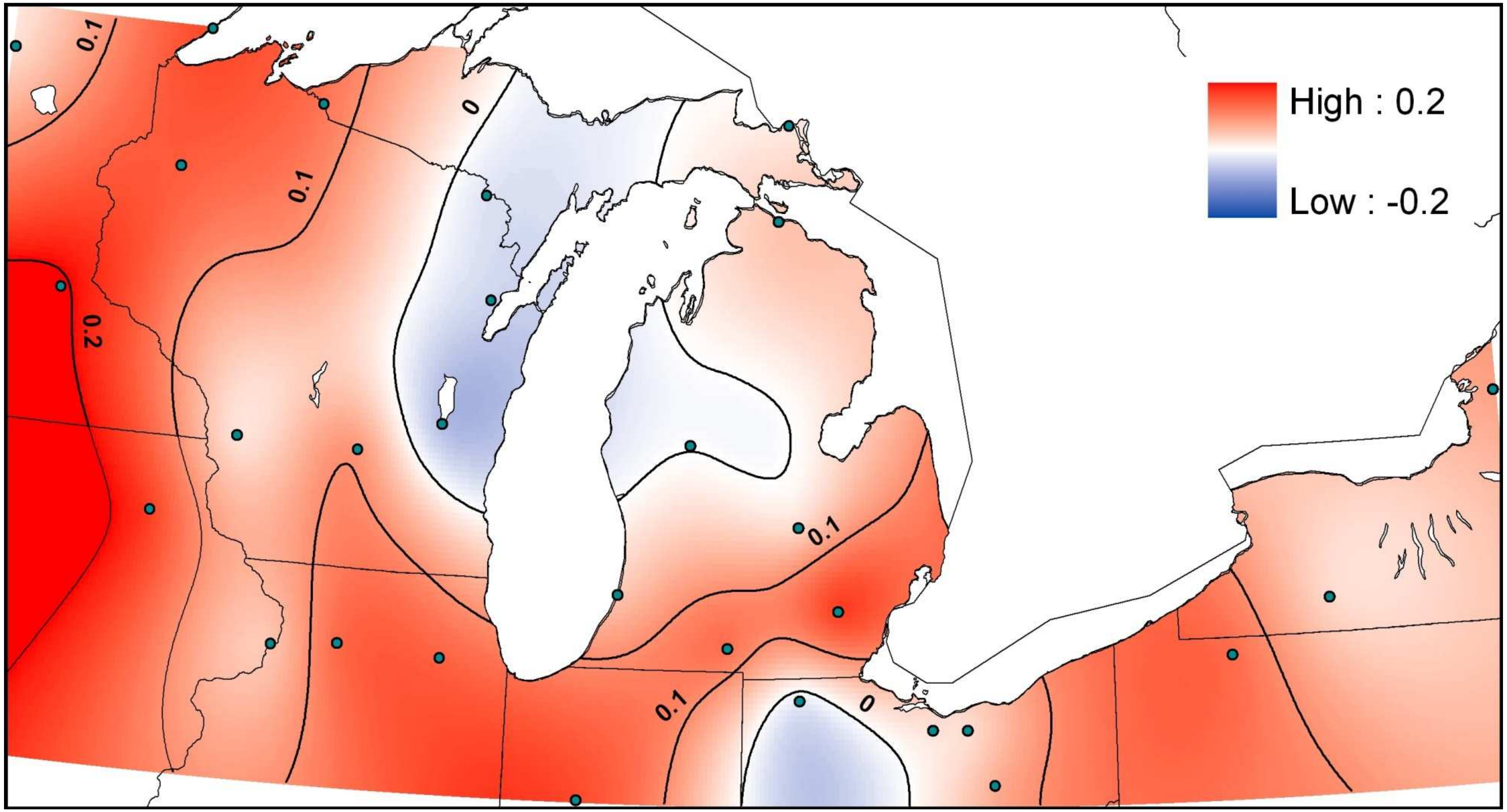

Figure 56: Rate of change, Minimum Yearly Soil Moisture value. Average of SL, L, and SiL, Wheat land cover, mm/year. Contours are 0.1 mm/year.

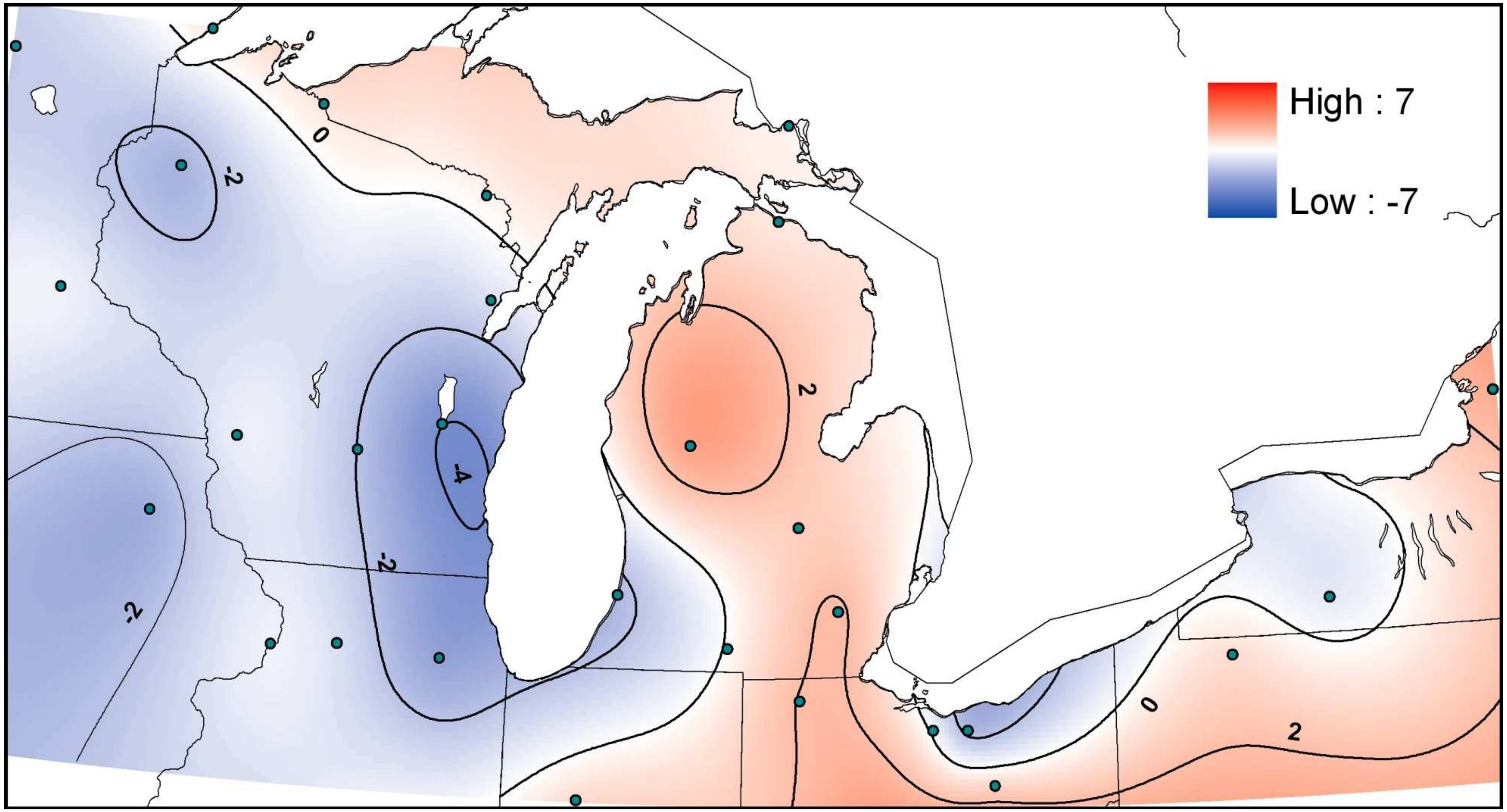

Figure 57: Rate of change, Rate of soil water recharge. Average of SL, L, and SiL. Corn land cover (μm/(days*year)). Contours are μm /(days/year).

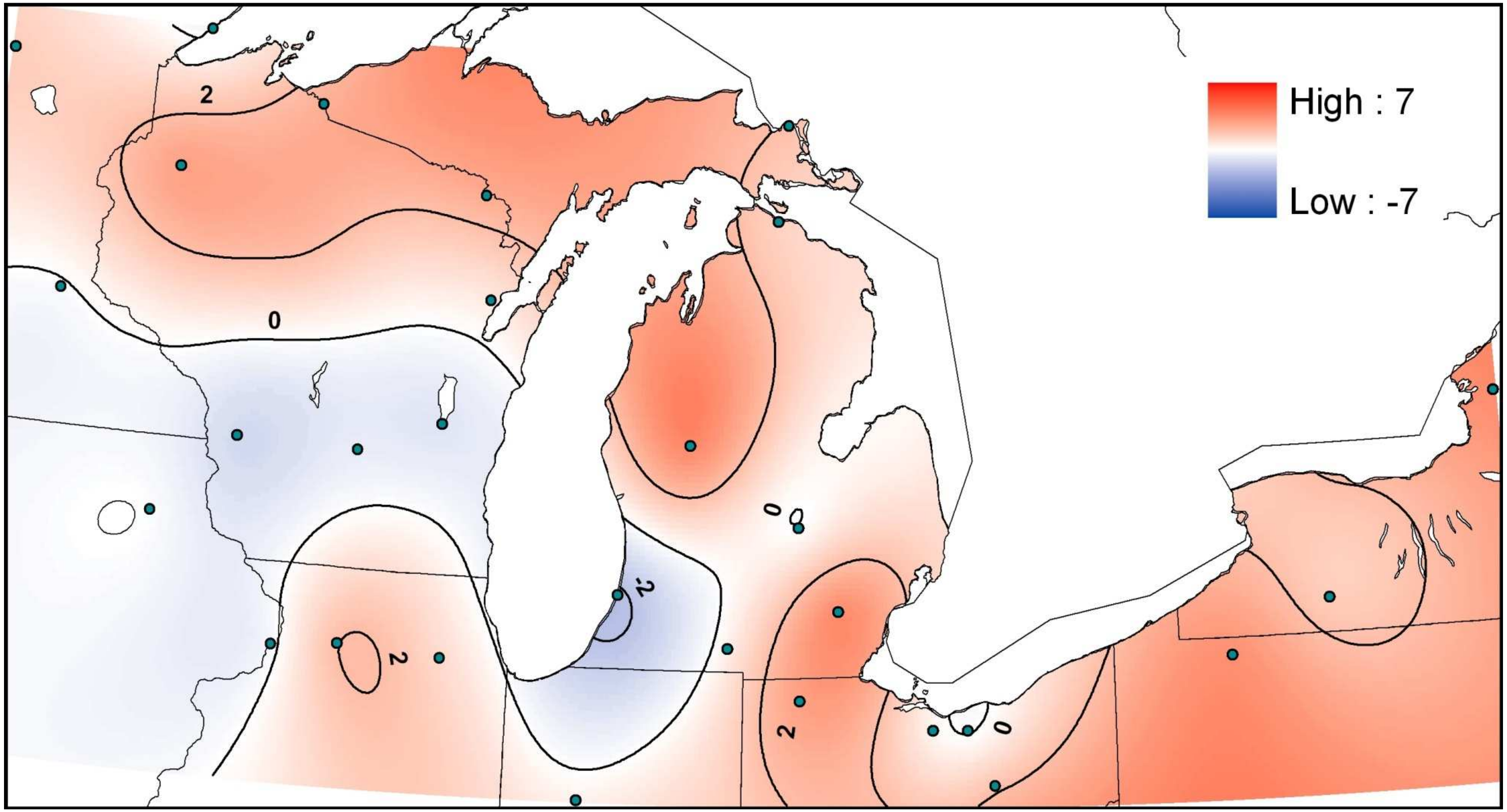

Figure 58: Rate of change, Rate of soil water recharge. Average of SL, L, and SiL. Forest land cover (μm/(days*year)). Contours are μm /(days/year).

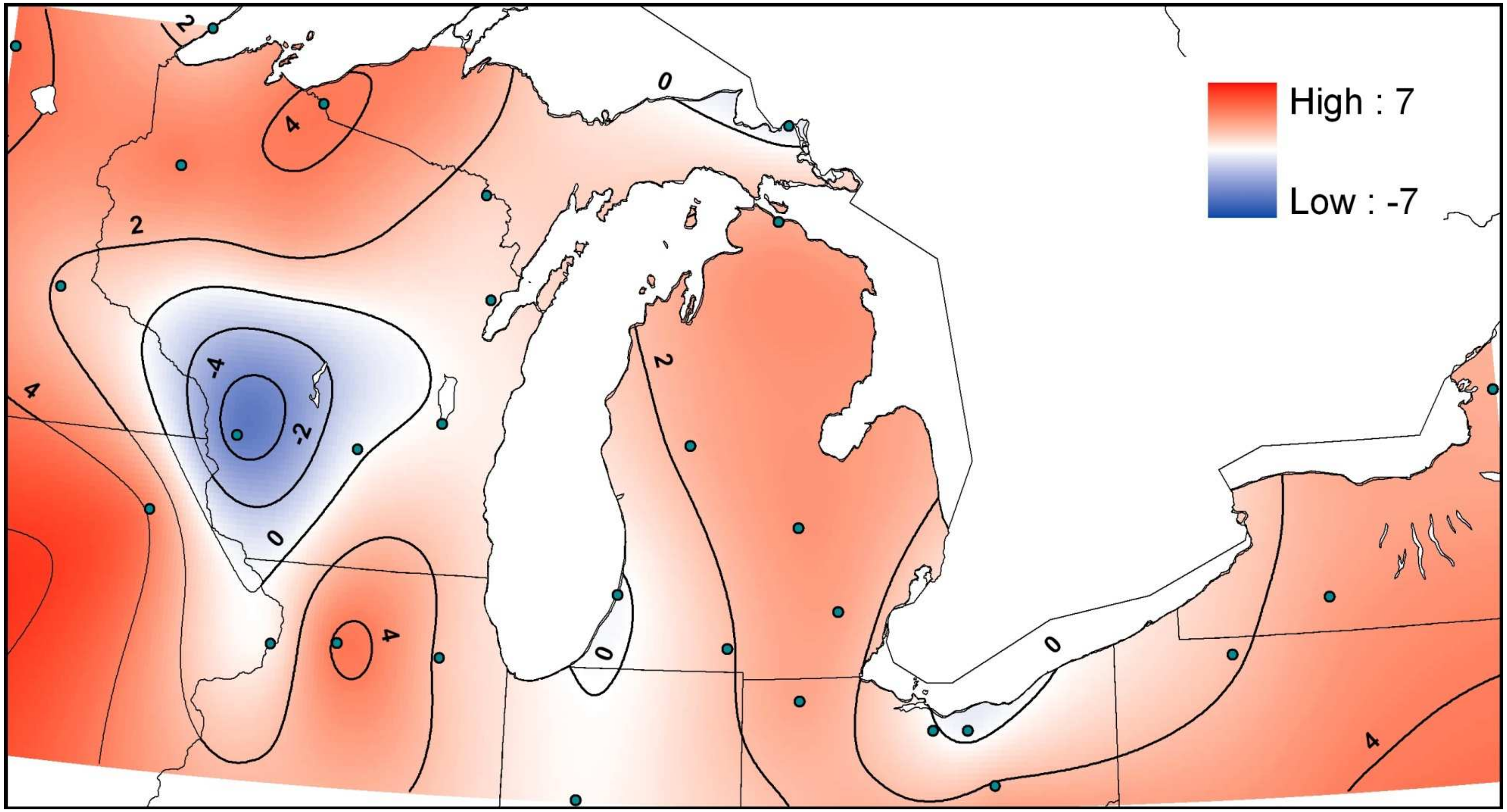

Figure 59: Rate of change, Rate of soil water recharge. Average of SL, L, and SiL. Pasture land cover (μm/(days*year)). Contours are μm /(days/year).

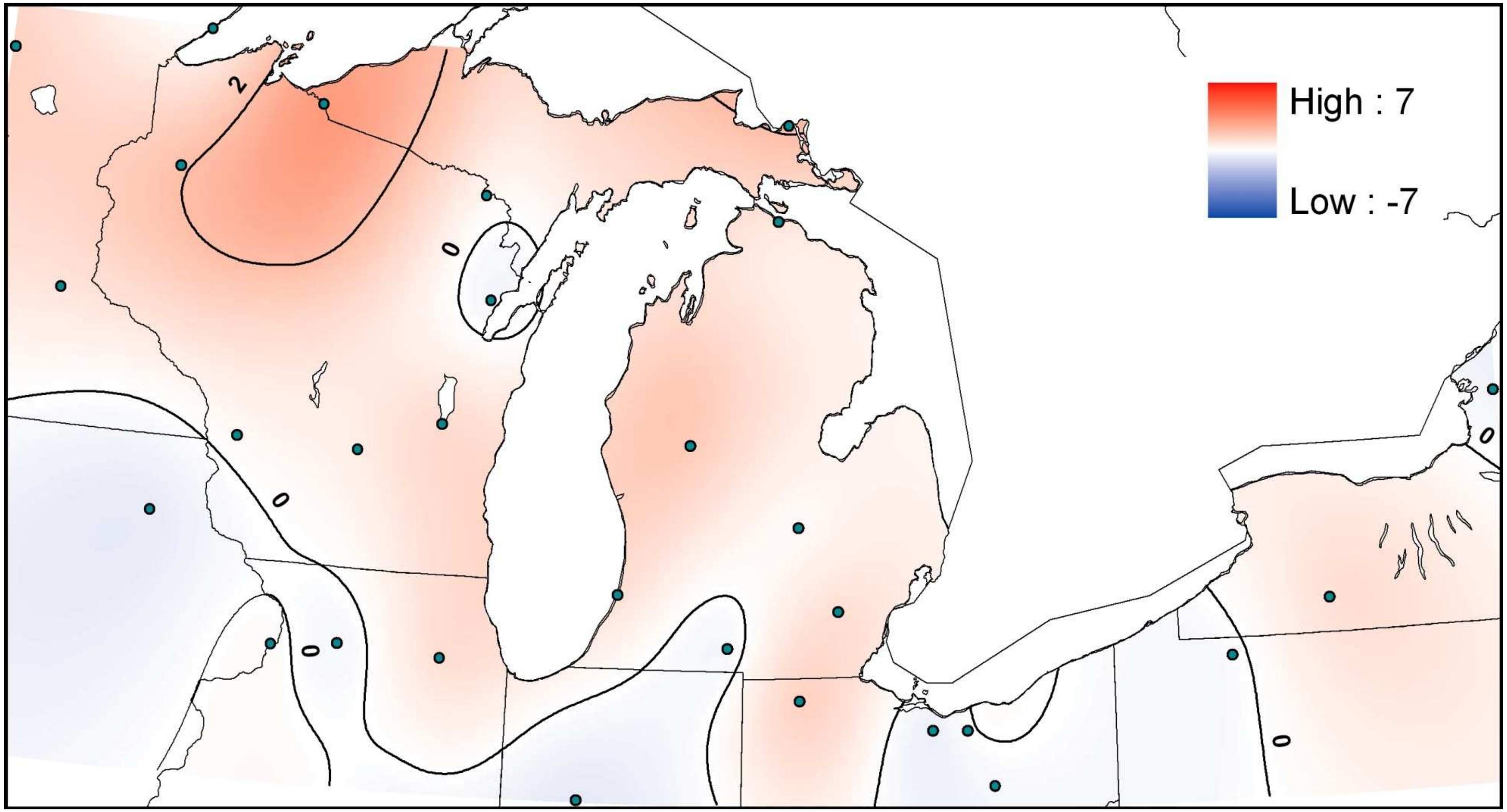

Figure 60: Rate of change, Rate of soil water recharge. Average of SL, L, and SiL. Urban land cover (μm/(days*year)). Contours are μm /(days/year).

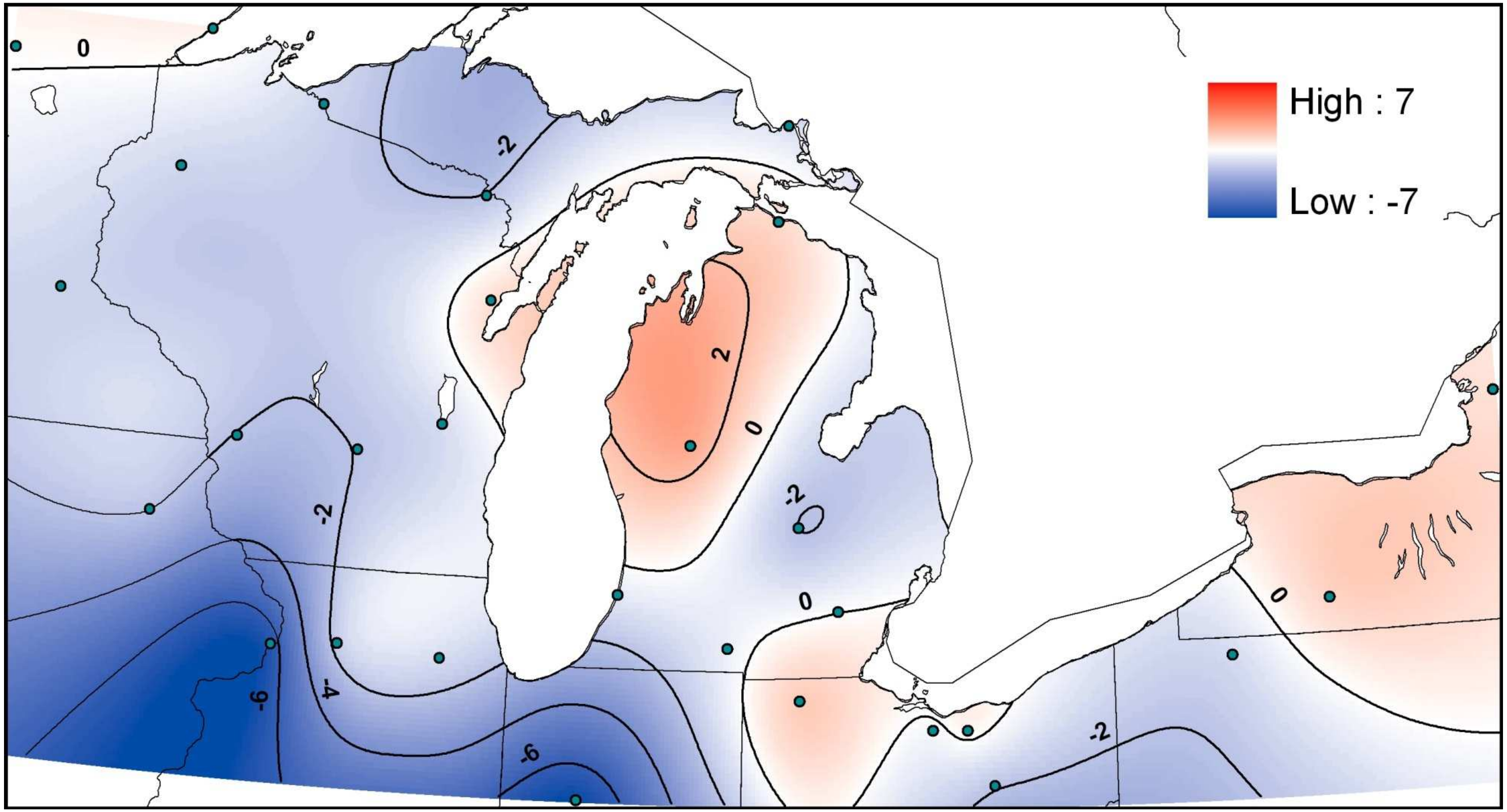

Figure 61: Rate of change, Rate of soil water recharge. Average of SL, L, and SiL. Wheat land cover (μm/(days*year)). Contours are μm /(days/year).

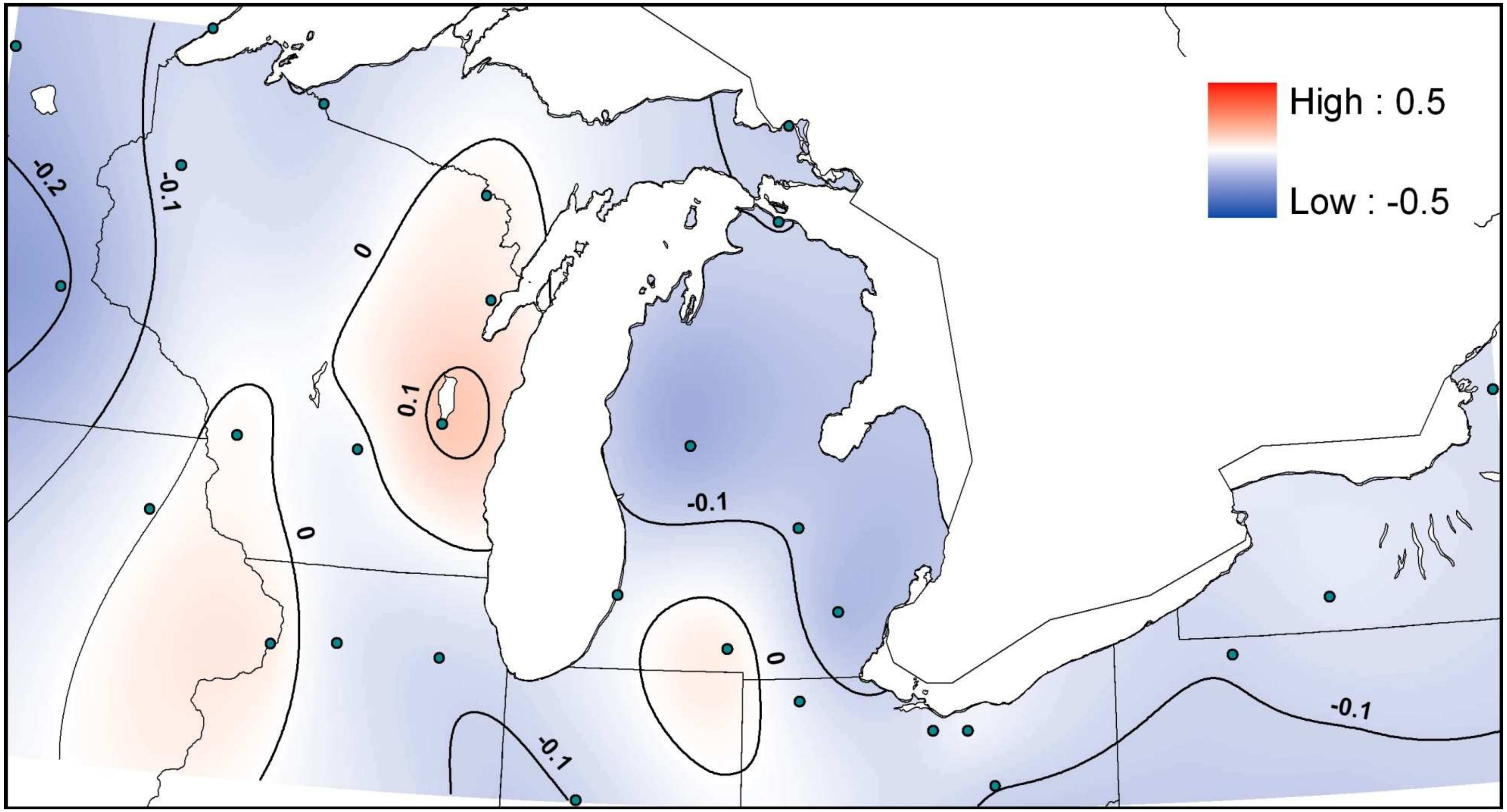

Figure 62: Rate of change, Day of Year of Recharge of soil moisture. Average of SL, L, and SiL. Corn land cover, days/year. Contours are 0.1 days/year.

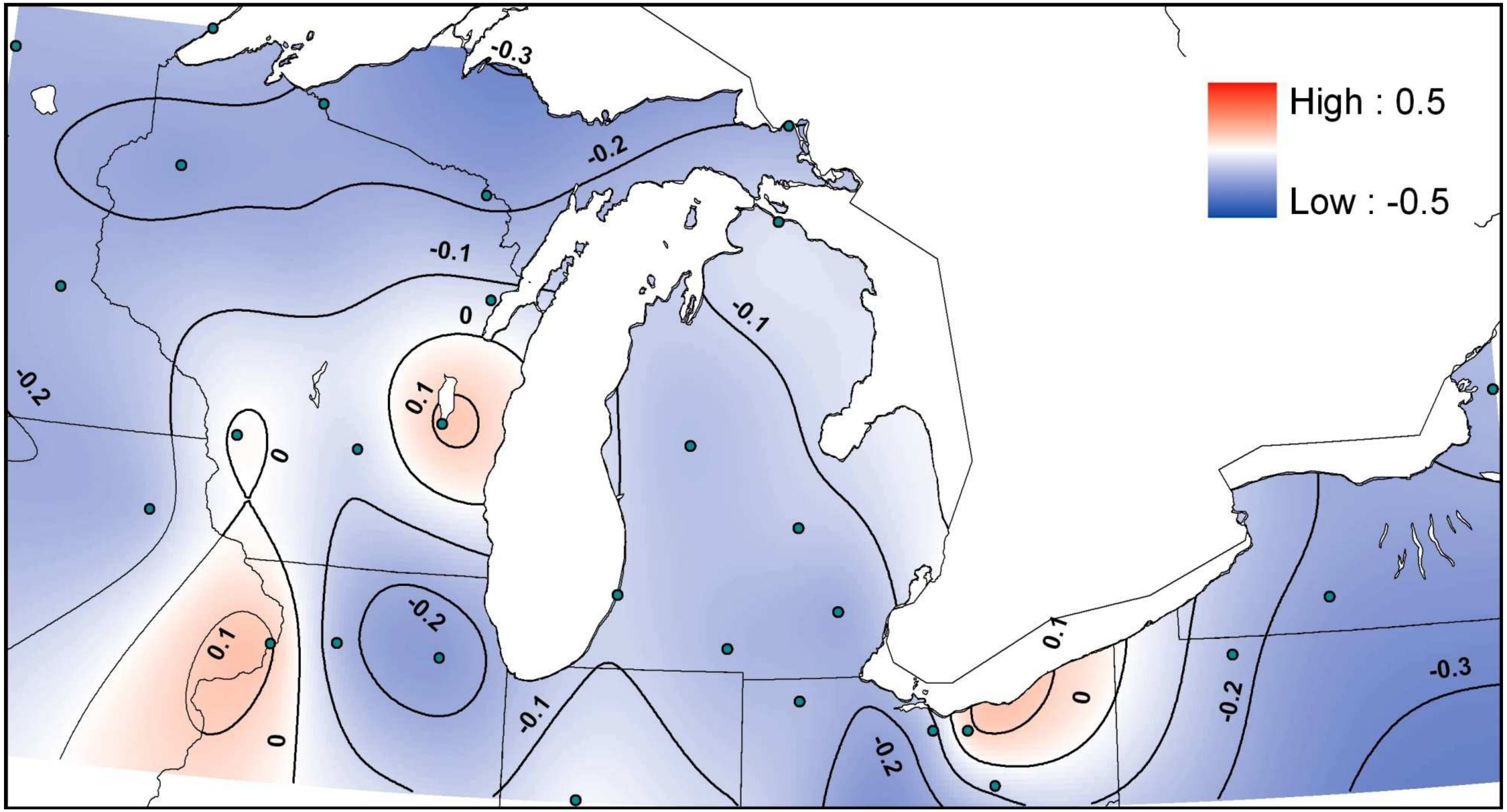

Figure 63: Rate of change, Day of Year of Recharge of soil moisture. Average of SL, L, and SiL. Forest land cover, days/year. Contours are 0.1 days/year.

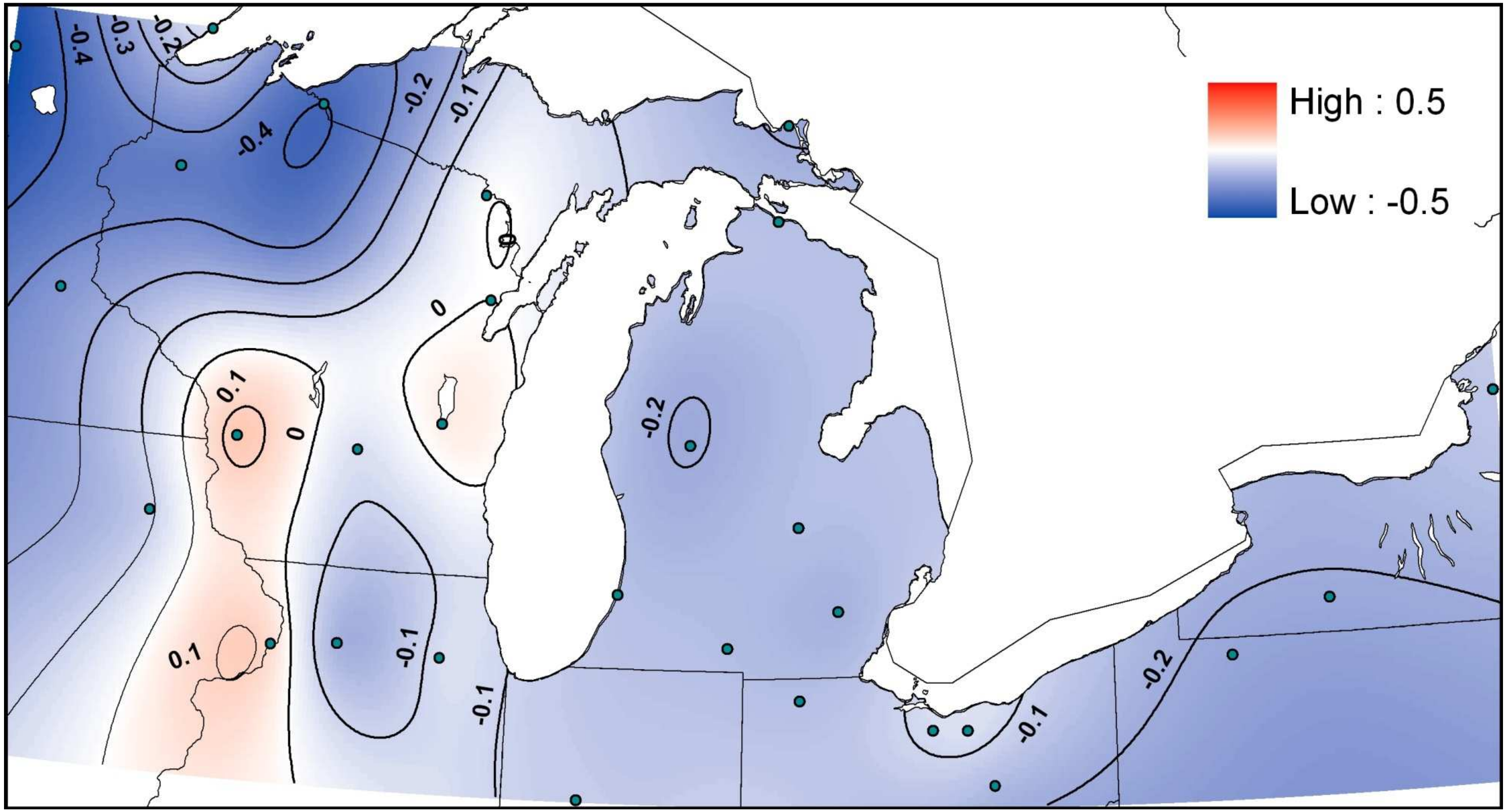

Figure 64: Rate of change, Day of Year of Recharge of soil moisture. Average of SL, L, and SiL. Pasture land cover, days/year. Contours are 0.1 days/year.

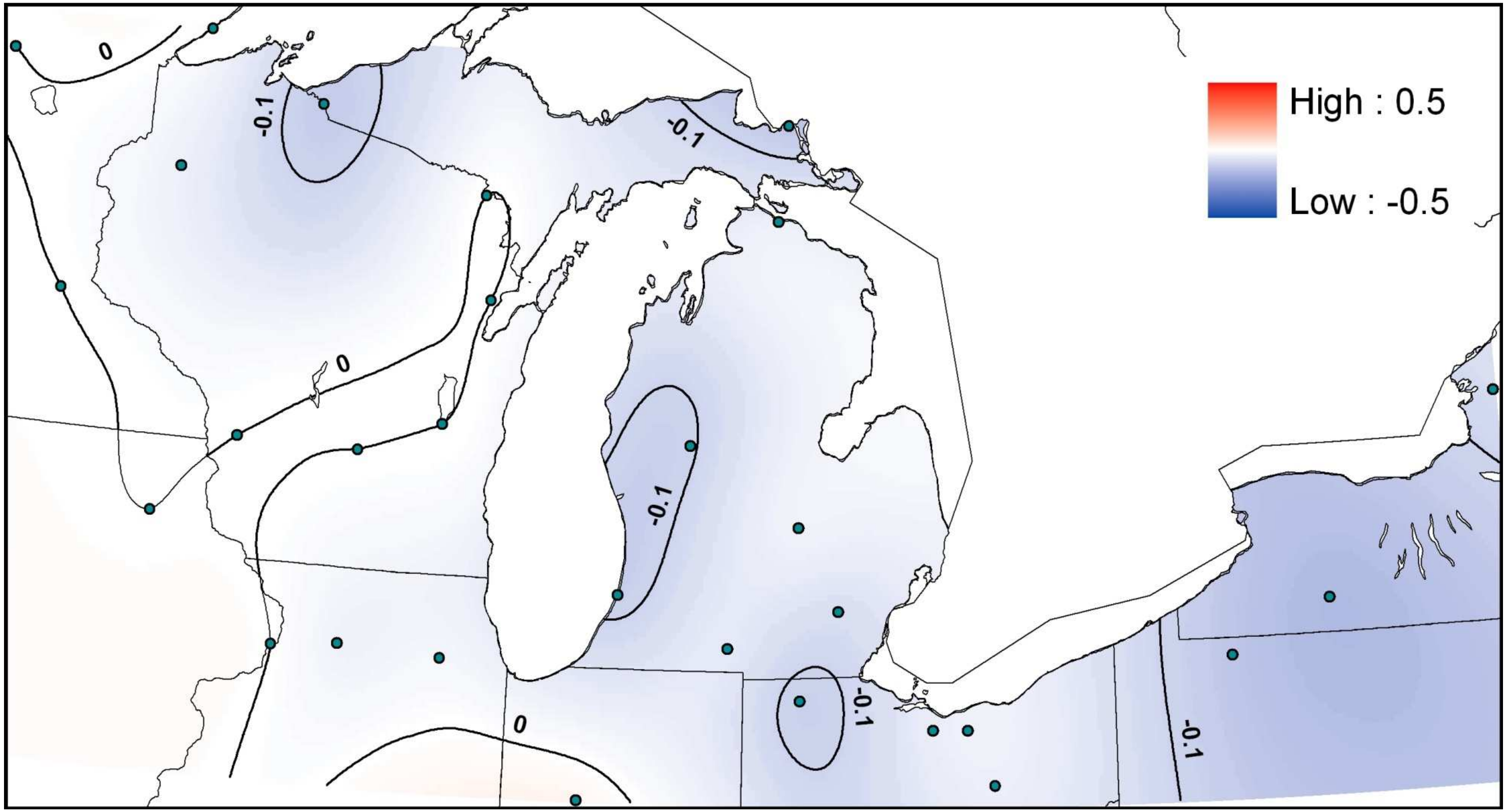

Figure 65: Rate of change, Day of Year of Recharge of soil moisture. Average of SL, L, and SiL. Urban land cover, days/year. Contours are 0.1 days/year.

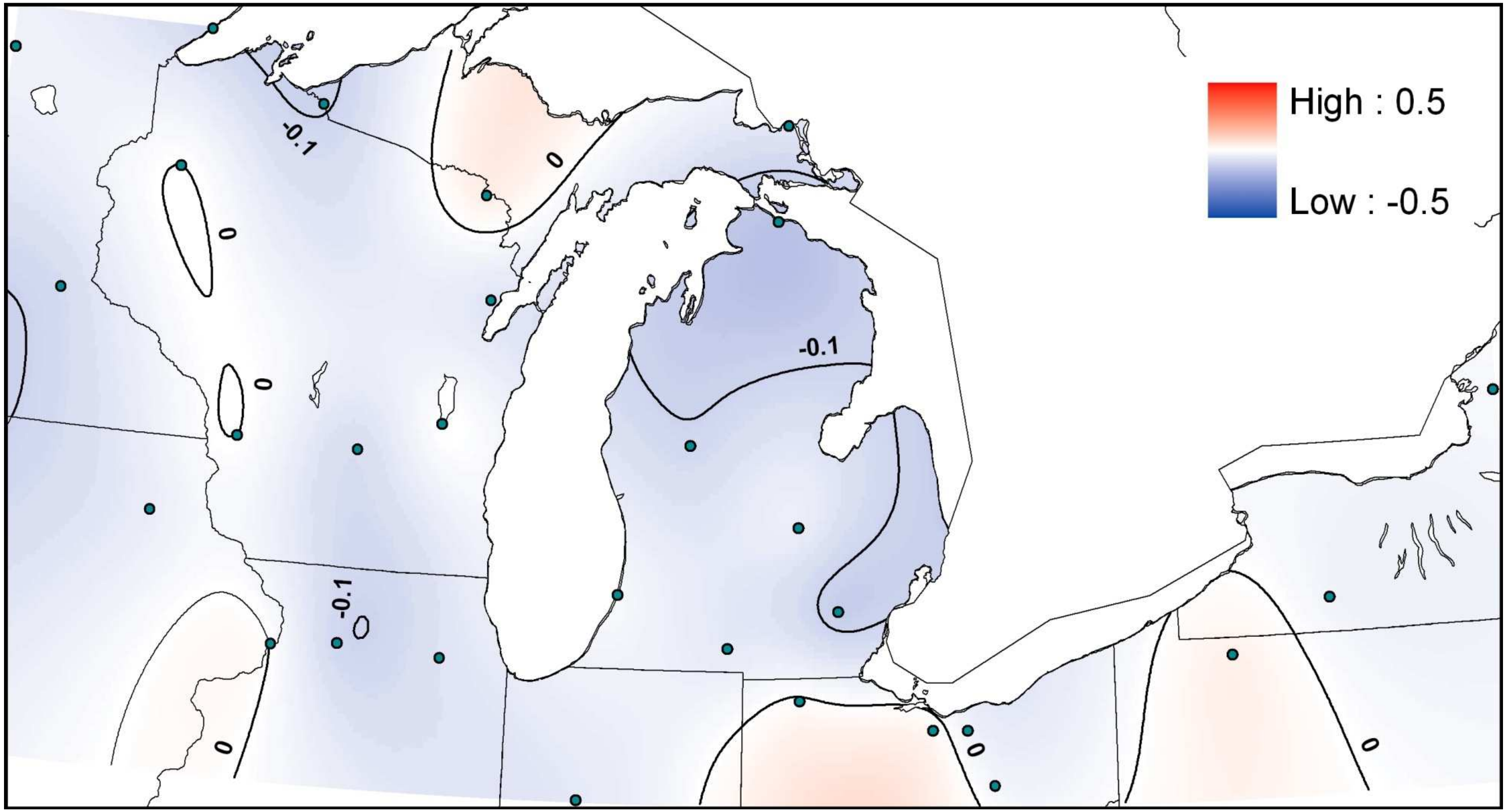

Figure 66: Rate of change, Day of Year of Recharge of soil moisture. Average of SL, L, and SiL. Wheat land cover, days/year. Contours are 0.1 days/year.

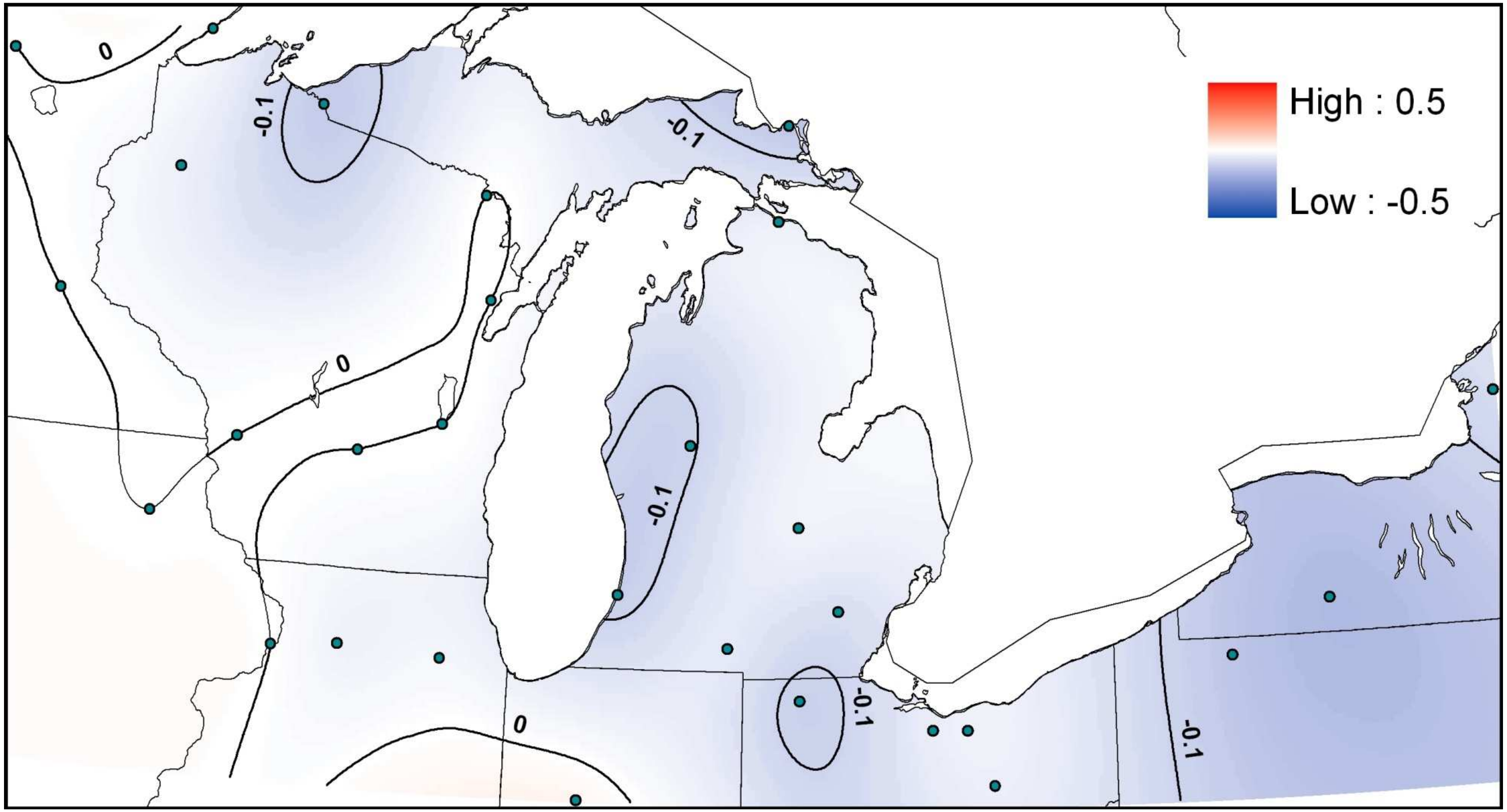

Figure 67: Rate of change, Soil Moisture Days. Average of SL, L, and SiL. Urban land cover, (soil moisture days / days) / year. Contours are 0.1 (soil moisture days / days) / year.

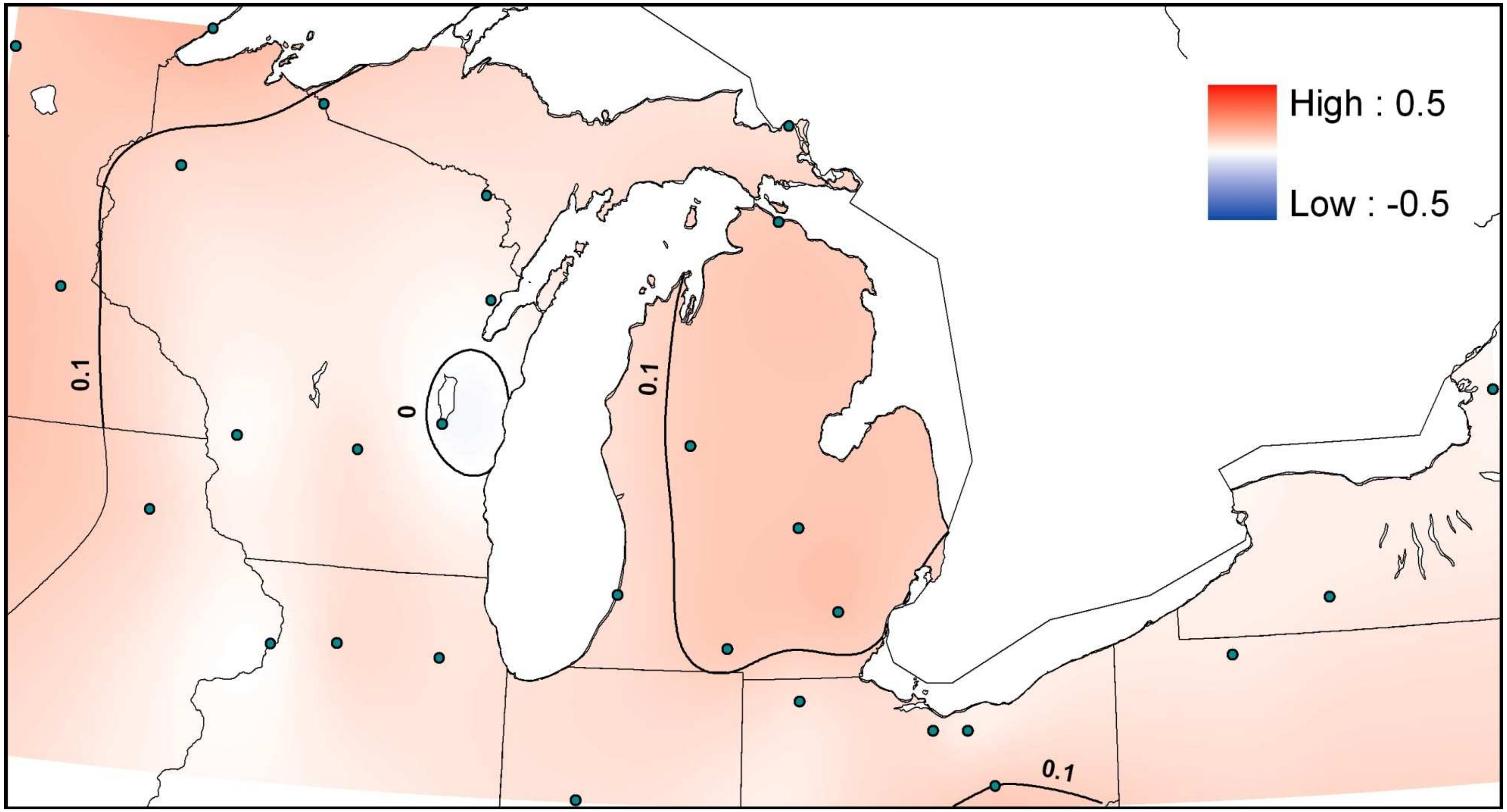

Figure 68: Rate of change, Soil Moisture Days. Average of SL, L, and SiL. Wheat land cover, (soil moisture days / days) / year. Contours are 0.1 (soil moisture days / days) / year.

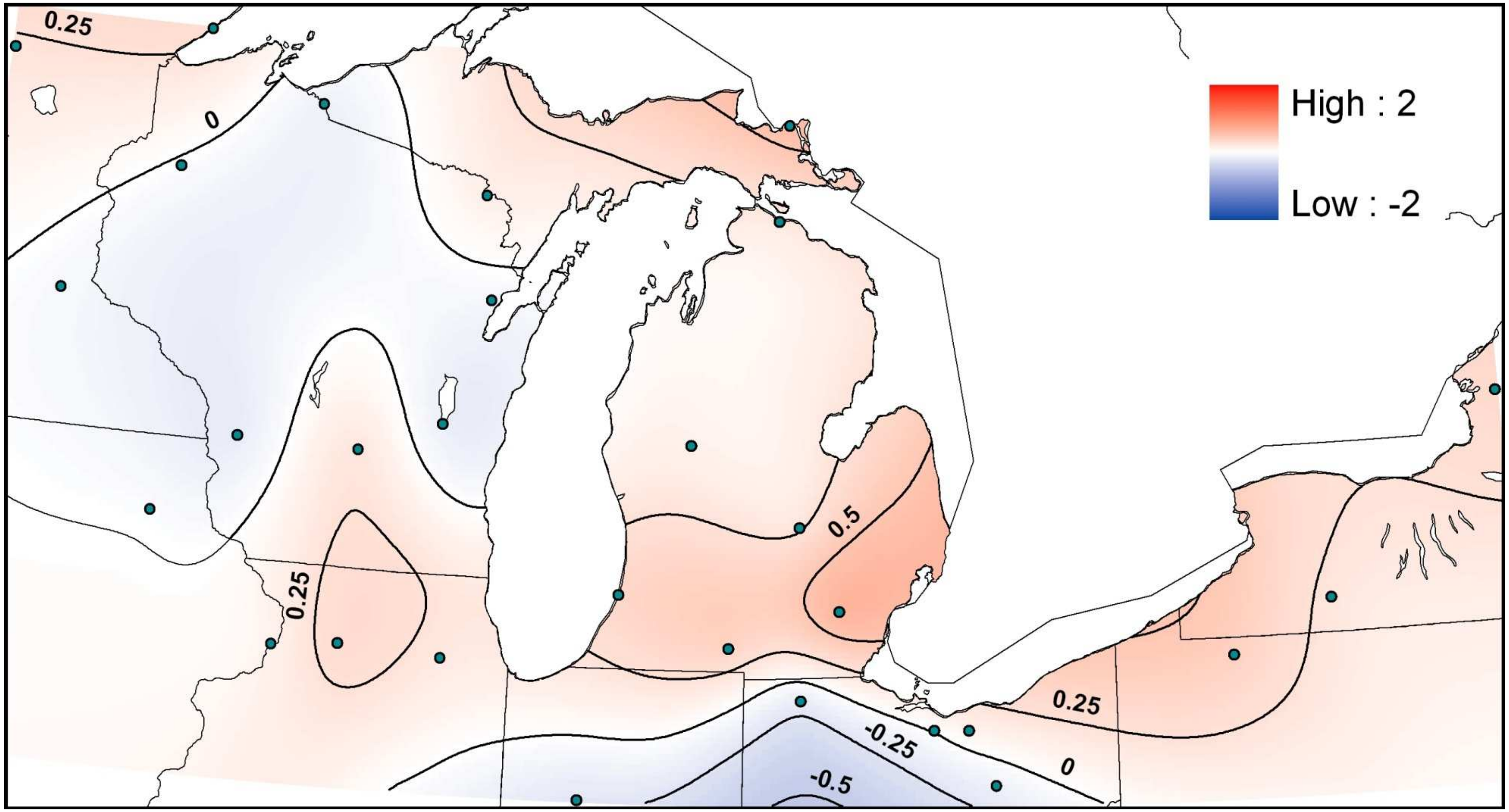

Figure 69: Rate of change: Winter Precipitation (mm/year) 1900-2008. Contours are at 0.25 mm/year intervals.

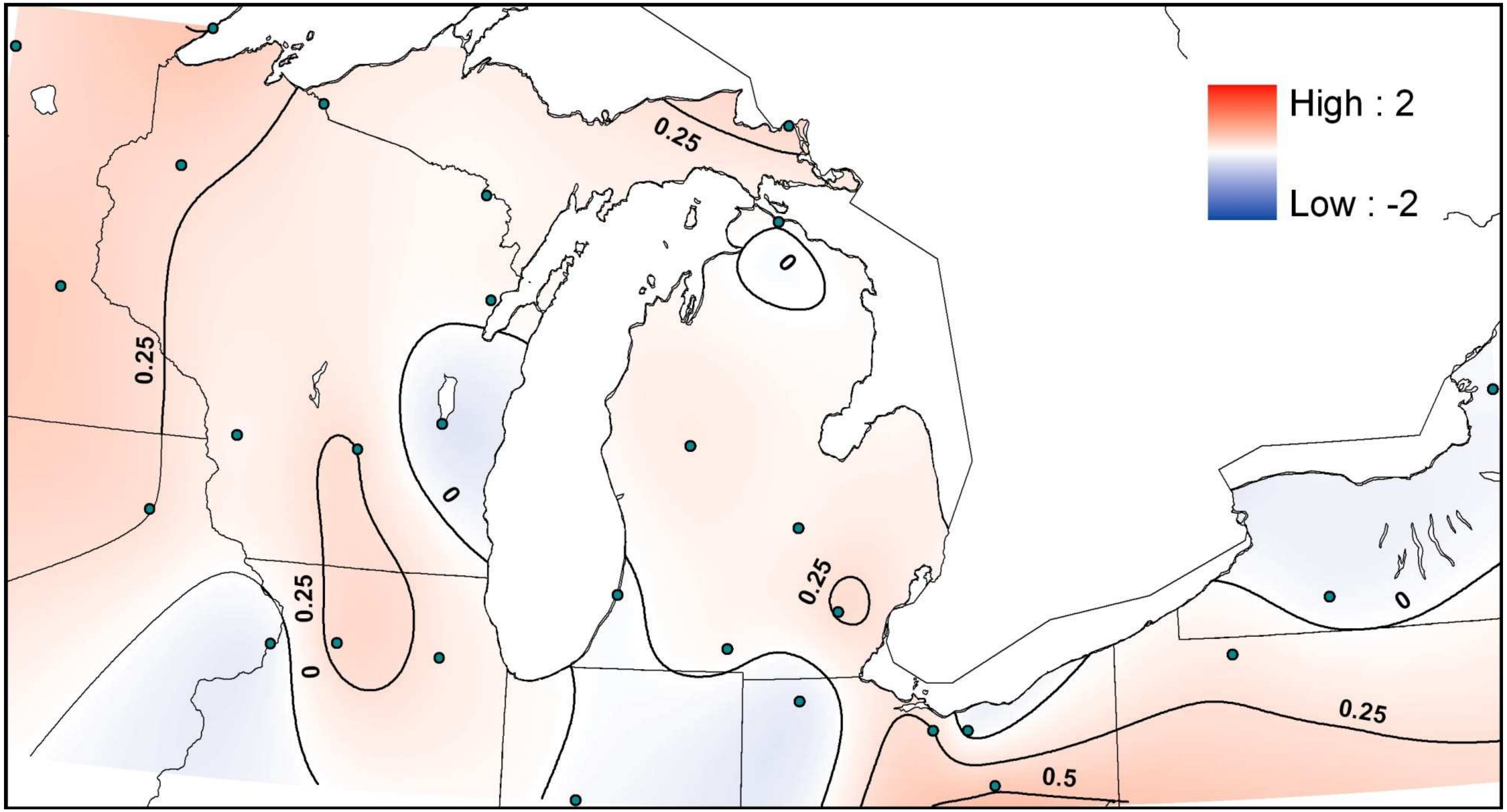

Figure 70: Rate of change: Spring Precipitation (mm/year) 1900-2008. Contours are at 0.25 mm/year intervals.

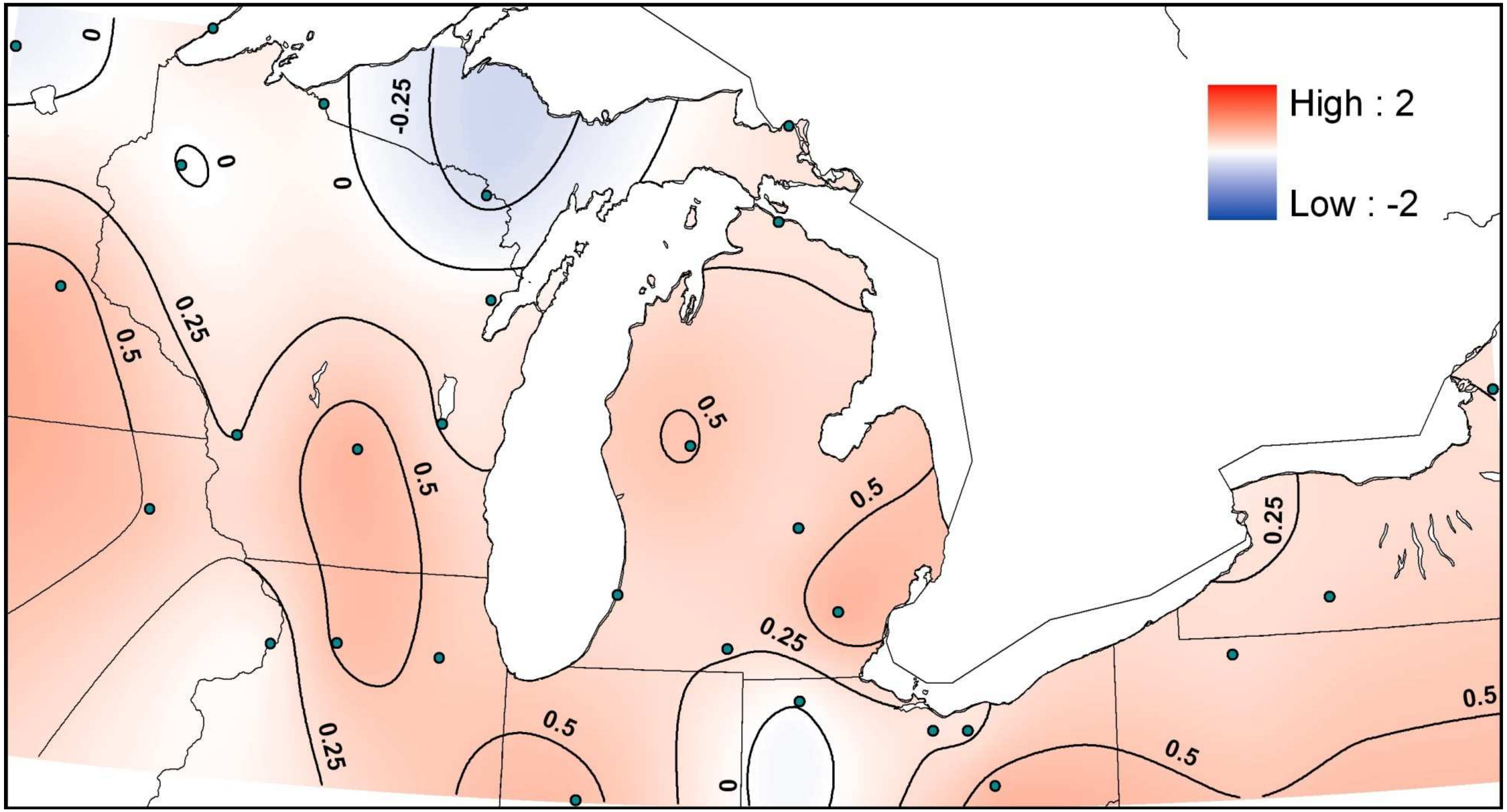

Figure 71: Rate of change: Summer Precipitation (mm/year) 1900-2008. Contours are at 0.25 mm/year intervals.

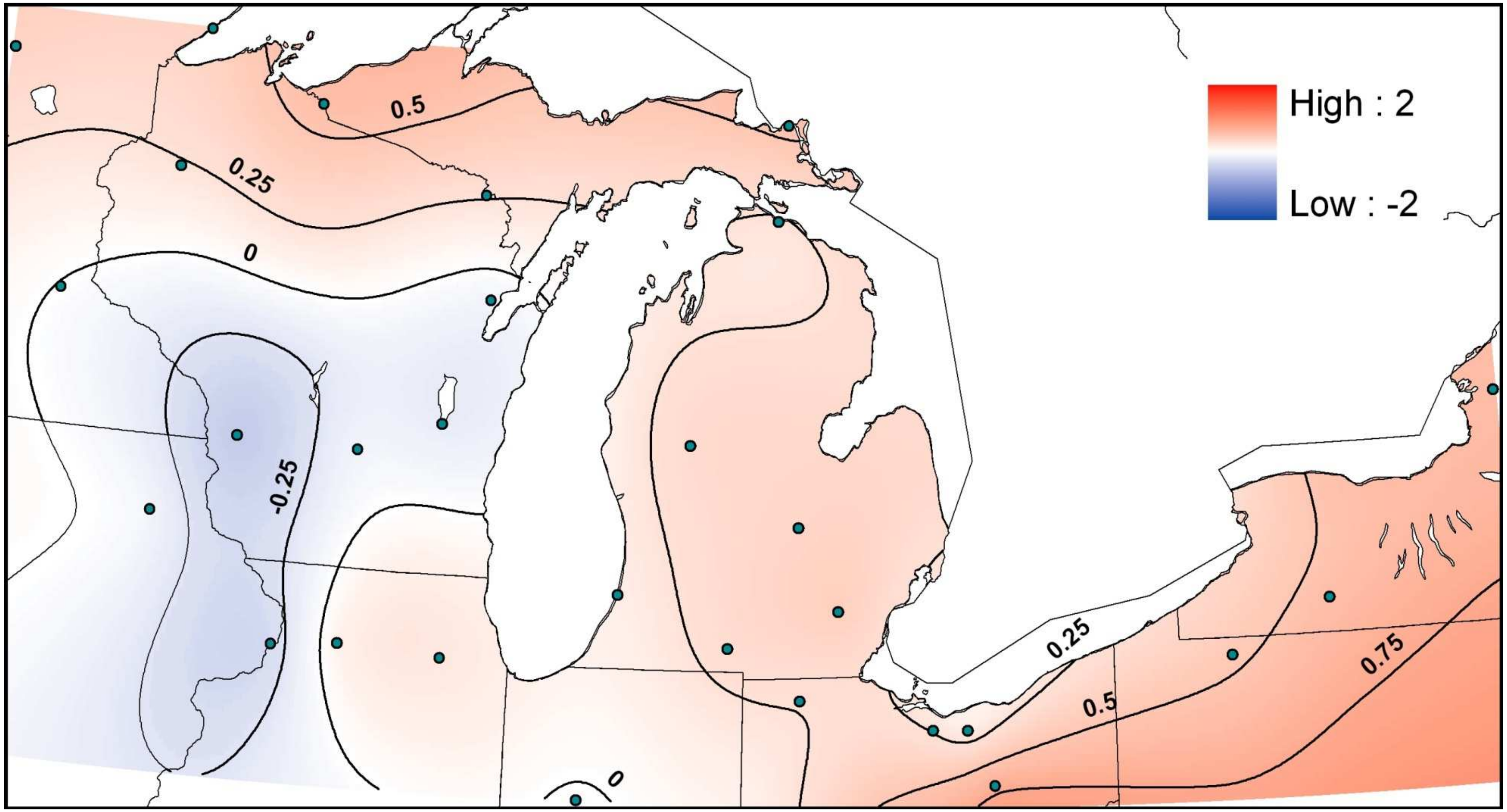

Figure 72: Rate of change: Fall Precipitation (mm/year) 1900-2008. Contours are at 0.25 mm/year intervals.

BIBLIOGRAPHY

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